Review & Evaluation of FEMA's Coastal Flood Risk Study

Data and Documents Review Technical Memorandum (Deliverable 4.1)
Task Order #1778-01

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Prepared for:

Palm Beach County
Discover the Palm Beaches... the Best of Everything

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
Rev A	5/1/2020	Draft	County review	DS	OK	DS
Rev B	8/18/2020	Draft	Comments incorporated	DS	GT	DS
Rev 0	10/1/2020	Final		DS	GT	DS

Executive Summary

The National Flood Insurance Program (NFIP) is a federal program that provides flood insurance to property owners within participating communities. Palm Beach County and a number of its communities participates in the program. The Federal Emergency Management Agency (FEMA) is responsible for administering the NFIP and as such periodically updates information on the flood hazards. The updated information is incorporated into FEMA's Flood Insurance Study (FIS) and Flood Insurance Rate Maps (FIRM) for a given study area.

FEMA is in the process of updating the FIS for the South Florida Study Area with the Coastal Flood Risk Study (SFL study), which was intended to reevaluate the coastal flood hazard originating from the Atlantic Ocean. Palm Beach County, along with Broward, Miami-Dade, and Monroe Counties, is located within the SFL study area. FEMA's study leveraged coastal numerical modeling and analyses to better define the coastal flood risks associated with storm surge. The document review presented herein was intended to identify specific elements of the study that may have misrepresented the water levels and mapping results with respect to Palm Beach County. The major elements are summarized below.

Validation Storm Selection

- Validation of the Simulating WAves Nearshore + ADvanced CIRCulation (SWAN+ADCIRC) model was based on five historical hurricanes; Betsy (1965), David (1979), Andrew (1992), Georges (1998), and Wilma (2005). Inclusion of these storms within the model validation may not have been appropriate given the magnitude of storm surge generated, the regional extents of the surge, the locations of gage measurements, and limited measured data. FEMA's statements within the documents also cast doubt as to the appropriateness of the selected storms.
- Inclusion of other validation storms in addition to (or in substitution of) those selected by FEMA should be considered. For example, Hurricanes Frances and Jeanne (2004) are potential storms that should be considered for the following reasons.
  - The storms provide a basis for representing storm surges along the Atlantic coastline of the study area, specifically within Palm Beach County.
  - The storms were used to validate the SWAN+ADCIRC model for FEMA's East Coast Central Florida (ECCFL) coastal study (2014). Inclusion of these storms within the SFL study may help improve agreement at the study area boundaries (Martin and Palm Beach county line).

SWAN+ADCIRC Model Validation

- Model validation did not account for the location of measured data with respect to the distances from storm tracks, the type of measured data (e.g. hydrographs and high water marks (HWM)), or the timing between measured and modeled peak water levels. Failure to do so may have negatively affected model validation and uncertainties and resulted in water levels that are not representative.
- Hurricane Wilma was the only common validation storm considered for both the SFL and ECCFL studies. The same water level gages were not used in both studies, which FEMA did not provide justification. The average difference of modeled water levels for the SFL study within the 60-mile segment of coastline common between the studies was 64% greater than the ECCFL study. The ECCFL study ultimately eliminated Hurricane Wilma to improve the model's capability to reproduce non-exiting storm conditions and because of increased uncertainty in the wind and pressure fields for exiting storms. Despite this, Hurricane Wilma was included in the SFL study.

Statistical Stillwater Elevations (SWEL)

- Model uncertainty was evaluated and used to statistically estimate the 1% SWEL within the study area. In developing inputs for the coastal hazard analysis, FEMA concluded that the 1% SWEL were high in some areas because of the model "uncertainty term and the combined storm frequency curves" for east and west coast storms used to define the 1% SWEL (Table 1.1, Reference #14). Review of FEMA's reports for the ECCFL study revealed that FEMA excluded west coast (exiting) storms citing that "exiting storms have a minimal effect on the low-frequency water levels" and "the presence of other uncertainties which influence the modeling results to a larger degree." FEMA reported that the influence of west coast storms on the SFL study was 0.25 feet (3 times greater than the ECCFL study) but opted to include them regardless.
- At the study area boundary between the SFL study and ECCFL study, discrepancies in the 1% SWEL were identified by FEMA. The 1% SWEL for the SFL study were higher by "1.7 feet along the open coast, 2.0 feet in the Intracoastal Waterway, and 2.0 to 4.2 feet up the Loxahatchee and North Fork Loxahatchee Rivers" (Table 1.1, Reference #12). FEMA identified a transition area and applied adjustments lowering the 1% SWEL within the northern 5 miles of the County to align the studies. Refinement to FEMA's approach to consider the entirety of Palm Beach County in adjusting the 1% SWEL appears justified. The alternate approach presented herein, if adopted by FEMA, would result in lower 1% SWELs within the County.

Coastal Hazard Analysis

- Revisions to the 1% SWEL may affect FEMA's evaluation of dune response.
- Review of FEMA's analysis and inspection of open coast transects suggested there may be opportunities to improve the consistency of the mapping of the VE Zone throughout Palm Beach County and to reflect the potential for wave overtopping and the landward limit of moderate wave action.
- FEMA's analysis of sheltered water (inland) transects excluded transects within the Lake Worth Lagoon south of the East Ocean Avenue bridge in Lantana to avoid inconsistencies in mapping Base Flood Elevations (BFE) along the eastern shoreline of the Lake Worth Lagoon. The inconsistencies were attributed to the larger starting wave conditions extracted from the SWAN+ADCIRC model results which appeared to be localized outliers as compared to the other areas of the lagoon. FEMA opted to rely on sheltered water transects within the lagoon to the north for mapping purposes as opposed to reviewing the SWAN+ADCIRC modeling to resolve the outlying starting wave conditions.

Subsequent tasks will review the model setups, inputs, outputs, and other data provide by FEMA to delve beyond the level of detail contained in FEMA's documents; this will provide Palm Beach County additional information and details regarding FEMA's SFL study.

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1. Introduction

The National Flood Insurance Program (NFIP) is a federal program that provides flood insurance to property owners within participating communities. Palm Beach County and a number of its communities participates in the program. The Federal Emergency Management Agency (FEMA) is responsible for administering the NFIP and as such periodically updates information on the flood hazards. The updated information is incorporated into FEMA's Flood Insurance Study (FIS) and Flood Insurance Rate Maps (FIRM) for a given study area.

FEMA is in the process of updating the FIS for the South Florida Study Area with the Coastal Flood Risk Study (SFL study), which is intended to reevaluate the coastal flood hazard originating from the Atlantic Ocean. Numerous documents have been generated by FEMA (and its mapping partner) for the updated SFL study, which are based on published FEMA guidelines as outlined in Table 1.1.

Palm Beach County, along with Broward, Miami-Dade, and Monroe Counties, is located within the South Florida Study Area. The documents in Table 1.1 were reviewed by Baird with respect to their applicability and appropriateness to Palm Beach County. The document review presented herein summarizes elements of the study that may warrant the County's attention. Elements are correlated to respective FEMA documents by the reference numbers assigned in the table below. The discussion is organized into the following broad categories.

- Validation Storm Selection
- SWAN+ADCIRC Model Validation
- Statistical Stillwater Elevations (SWEL)
- Coastal Hazard Analysis

It should be noted that the discussion herein does not attempt to document all elements that were considered during our review nor does it attempt to provide resolutions to these elements, but rather provides information intended to improve the accuracy, consistency, and reliability of FEMA's SFL study in simulating water levels and mapping flood risks. Task 5 will review the model setups, inputs, outputs, and other data provided by FEMA to delve beyond the level of detail contained in FEMA's documents; this will provide the County additional information and details. Coastal analysis and modeling to evaluate the impact and sensitivity of the elements on FEMA's overall SFL study is beyond Baird's scope of work.

Table 1.1: List of FEMA Documents.

FEMA Document		Date	Description	Reference #
SFL Coastal Study Documents				
Coastal Discovery Report		Apr 2015	Presents available data and information considered by FEMA for inclusion in the updated coastal study.	[1]
Intermediate Data Submittal (IDS) Reports				
#1	Section 1 - Technical Approach	Nov 2014	Introduces the major technical study components contained in IDS Report #1, Sections 2-7.	[2]
	Section 2 - Digital Elevation Model (DEM)	Mar 2016	Discuss topographic and bathymetric data sets, DEM development, and creation of the finite element model mesh utilized in the SWAN+ADCIRC modeling, WHAFIS modeling, and coastal hazard analyses.	[3]
	Section 3 - Validation Storm Selection	Feb 2015	Presents wave and water level data sets and the methodology applied to develop the studys validation storm suite for the SWAN+ADCIRC modeling.	[4]
	Section 4 - Study Area & Site Reconnaissance	May 2015	Details site reconnaissance performed and the procedure followed to identify coastal structures and to delienate the primary frontal dune (PFD).	[5]
	Section 5 - JPM-OS Probablistic Model Development	Jun 2015	Documents the storm climatology and initial probabilistic model development.	[6]
	Section 6 - Tropical Analysis & Forcing Development	Feb 2015	Presents the methodology applied to develop wind and pressure fields as inputs to the SWAN-ADCIRC modeling.	[7]
	Section 7 - Hydrodynamic & Wave Model Development	Jan 2016	Details the wave and hydrodynamic storm surge model and mesh development methods.	[8]
#2	Section 1 - Wave & Hydrodynamic Model Validation	Feb 2017	Describes the methodology and results of the wave and hydrodynamic modeling validation.	[9]
	Section 2 - JPM-OS	Oct 2016	Describes development of the representative stor set and associated annual recurrance rates (return period) of storms.	[10]
#3	Section 1 - Production Runs	Jun 2018	Describes the SWAN+ADCIRC modeling of the synthetic storms developed as part of the JPM-OS analysis. The modeling resulted in total maximum water levels and wave conditions for return period storms.	[11]
	Section 2 - Low-Frequency Analysis	Jul 2018	Documents the methodology used to define still water elevations (SWEL) throughout the SWAN+ADCIRC modeling domain for low-frequency (2-, 1-, and 0.2-percent-annual-chance) storm events.	[12]
	Section 3 - Regional Fequency Analysis of Tide Gage Water Levels	Jul 2019	Documents the methodology used to define still water elevations (SWEL) throughout the SWAN+ADCIRC modeling domain for high-frequency (50-, 20-, 10-, and 4-percent-annual-chance) storm events.	[13]
#4,5	Coastal Hazard Analysis	Oct 2019	Decribes the analyses of overland wave propagation, wave runup, wave overtopping, coastal structures, storm induced erosion used to define special flood hazard araes (SFHA) and delineate flood zones boundaries.	[14]
Preliminary Flood Insurance Study (FIS)		Dec 2019	Summarizes the general framework of the study, engineering methods considered in the study, and mapping methods.	[15]
Preliminary Flood Insurance Rate Map (FIRM) Panels		Dec 2019	Maps depicting SFHA, flood zones, and base flood elevations (BFE) resulting from the study. Maps provide a level of detail that individual building and parcels can be identified.	[16]
FEMA Guidance Documents				
Atlantic Ocean & Gulf of Mexico Coastal Guidelines Update		Feb 2007	Technical guidance governing the breadth of the modeling and analysis for coastal study updates.	[17]
Guidance for Coastal Flood Hazard Analysis & Mapping (CFHAM)				
Sheltered Waters		Feb 2008	Guidance for analyzing flood harzards (primarily 1-percent-annual chance- storm events) within sheltered water areas.	[18]
Overland Wave Propagation		Nov 2015	Guidance on applying the WHAFIS model, defining input parameters, and interpreting model results.	[19]
Erosion		Feb 2018	Guidance on methods available to estimate profile changes for erodible shorelines due to storm events.	[20]
Coastal Floodplain Mapping		Nov 2019	Guidance on delineating coastal flood zones and defining BFE's.	[21]
Coastal Water Levels		May 2016	Guidance on extracting stillwater level (SWL) data from measured water levels and on determining SWL where storm surge processes dominate.	[22]
Coastal Structures		Nov 2019	Guidance on methods available to analyze the stability and effects of coastal structures during the 1-percent-annual-chance storm event.	[23]
Coastal General Study Considerations		Nov 2019	Guidance provides an overview of coastal flooding processes and describes general considerations for FEMA coastal flood hazard studies.	[24]
Determination of Wave Characteristics		Feb 2019	Guidance on determining wave characteristics that are required for a coastal hazard analysis.	[25]
Wave Height Analysis for Flood Insurance Studies (WHAFIS)				
WHAFIS Technical Documentation Version 3.0		Sep 1988	User manual for the WHAFIS model.	[26]
Supplementary WHAFIS Documentation Version 4.0		Aug 2007	Supplemental information for a later version of the WHAFIS model.	[27]

2. Validation Storm Selection

Coastal storm events can result in elevated water levels known as storm tides. Storm surge is the difference between storm tides and underlying astronomical tides and is affected by the combined effects of waves, currents, and water levels, among other factors. The FEMA SFL study utilized a coupled wave model and hydrodynamic model (SWAN+ADCIRC model) to simulate coastal storm surge. The SWAN spectral wave model was used to develop the offshore and nearshore wave climate, while the ADCIRC hydrodynamic model simulated currents and water levels. Coupling of the models allows for wave-induced water level changes and its effects on storm surge to be accounted for simultaneously during model simulations. The SWAN+ADCIRC model requires that a model mesh be developed for the study area and a subsequent validation "demonstrates satisfactory model performance – without consistent bias to underestimate or overestimate water levels" [2]. Thus, validation requires selection of representative storm events, which is detailed in FEMA's Intermediate Data Submittal (IDS) Report 1, Section 3 [4].

The following storms were selected by FEMA to validate the SWAN+ADCIRC model; storm tracks are shown in Figure 2.1.

- Hurricane Betsy (1965)
- Hurricane David (1979)
- Hurricane Andrew (1992)
- Hurricane Georges (1998)
- Hurricane Wilma (2005)

FEMA's SFL study identified the following criteria to guide the selection of validation storms [4]:

- Storms that made landfall within the project area, exited within the project area, or bypassed near the study area.
- Storms that resulted in significant surge (approximately greater than 3 feet) within the project area.
- The availability of water level data points available for each storm and their spatial distribution throughout the study area.
- The density of wave data points available for each storm and their spatial distribution throughout the study area. (It should be noted that this criterion was later eliminated from the study given the lack of wave data near the study area).
- Storms occurring between 1950 and 2014 and that passed within 200 nautical miles of Miami, Florida. 1950 represents the year of implementation of more sophisticated storm data collection techniques.
- Storms with central pressures of 980 millibars or lower at landfall, land exit, or at the point of closest approach to the study area. Extra-tropical systems were not included.
- Storms that increase the spatial distribution of storm surge validation over the study. In other words, ensuring the model is equally valid for all parts of the study area.
- Historical significance of the storm (i.e. storms identified by local residents as major events impacting the study area).

In summarizing its basis for selecting validation storms, FEMA defined one basis as being "water level records are available at more than 15 stations" [4]. This was inferred as FEMA's threshold for satisfying its criteria regarding availability of water level data and spatial distribution throughout the study area (3rd bullet in the list above). According to the information presented, National Oceanic Atmospheric Administration (NOAA), United States Army Corps of Engineers (USACE), United States Geological Survey (USGS), and South Florida Water Management District (SFWMD) stations within the study area were evaluated. Figures presented by FEMA cross-reference the available stations with respect to the selected storm events. NOAA's Key West station, a data point (not a time series) from NOAA's Miami Beach station, and four USGS stations in Broward County were identified for Hurricane Betsy in 1965. NOAA's Key West station and six SFWMD stations throughout the east coast of the study area were identified for Hurricane David in 1979. The available stations for Hurricanes Betsy and David were less than the 15-station threshold and highwater mark (HWM) data was not available to supplement the station data for either storm.

Subsequently, FEMA makes the following statements calling in to question the appropriateness of selected validation storms in performing the model validation of water levels.

- While Hurricanes Betsy, Andrew, and Wilma "produced significant surge" near the landfall locations, the storms "do not provide wide coverage of recent surge levels in the study area as they did not produce significant surge in southern Palm Beach or Broward Counties or in the Florida Keys" [9].
- With respect to Hurricane Betsy, "very little observed data are available for validation purposes" [9].
- "Inclusion of Hurricanes David and Georges recognized the need to evaluate multiple storms and storms with landfall locations that cover the study area. However, these storms do not represent ideal validation cases as their surge values occur well below the 1%-annual-chance levels targeted by the modeling effort" [9].
- FEMA stated that while NOAA's Key West station provides the longest record in study area and is "in a good location for storms that move through the Gulf of Mexico, the location of the Key West station does not make it a suitable station to capture the maximum surge levels for storms that impact the Atlantic coastline" [4].
- FEMA reported modeling challenges for Hurricane Andrew associated with "wind field development due to extremely strong winds, small-scale spatial variations (wind micro-structures), and failure of local recording stations" [9]. FEMA performed extensive sensitivity analyses on winds and storm tracks during model validation, but discrepancies were not resolved.

Inclusion of other validation storms in addition to (or in substitution of) those selected appears warranted in order to improve FEMA's model validation and representation of storm surge throughout the study area. FEMA should have included more recent storms with storm tracks adjacent but in close proximity to the study area, higher storm surge values, and greater spatial distribution of measured water level data. For example, Hurricanes Frances and Jeanne are potential storms that should be considered for the following reasons.

- The storms provide a basis for representing storm surges along the Atlantic coastline of the study area and in particular Palm Beach County. The hurricanes occurred more recently (September 2004) as compared to the selected storms and more robust measured water level data is available. The more northerly track of the hurricanes (Figure 2.2) would reduce the dependence on the Key West station while representing storm surges experienced in the northern portion of the study area.
- The storms passed within 200 nautical miles of Miami Beach. The hurricanes both made landfall immediately north of the study area in Martin County at similar locations as Hurricane David, which was a selected validation storm.
- The storms were of historical significance to the study area as reported by FEMA. The hurricanes resulted in "fatalities, property damage, power outages, and flooding across Palm Beach County" and that Hurricane Frances resulted in "approximately $34,000,000 in property damage in Miami-Dade County" [1].
- The storms passed closer to a location of measured wave data (NOAA's wave buoys located offshore of Cape Canaveral) than the other selected validation storms. It is anticipated that the hurricanes would provide an opportunity to perform validation of modeled wave conditions, which was not possible for the selected storms (see Section 3).

- The storms were used to validate the SWAN+ADCIRC model for FEMA's East Coast Central Florida (ECCFL) coastal study (2014). Inclusion of Hurricanes Frances and Jeanne as validation storms for the SFL study would likely provide added value in improving agreement with the ECCFL study (see Section 4).

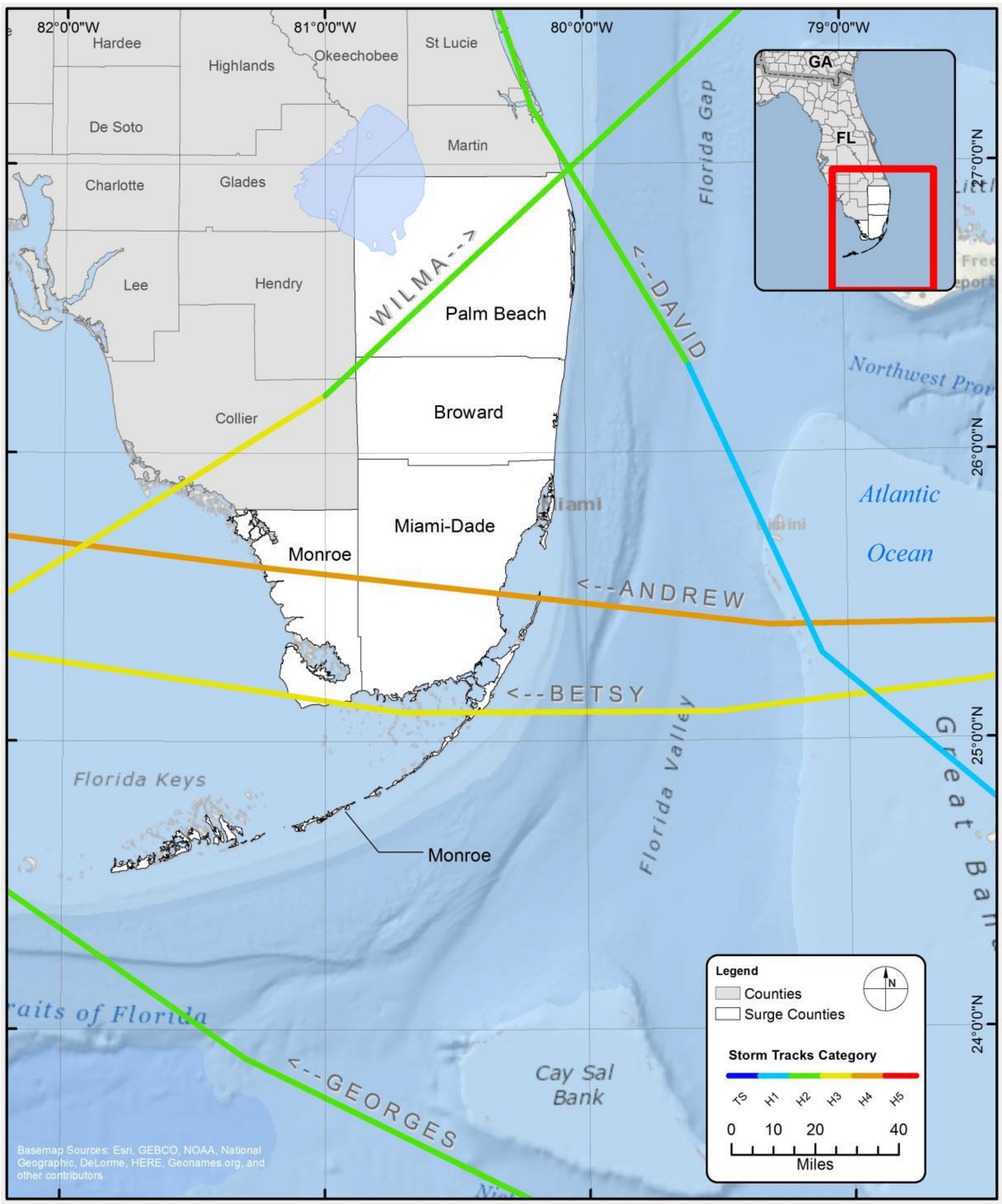


Figure 2.1: Tracks of selected Validation Storms (FEMA, 2015; [4]).

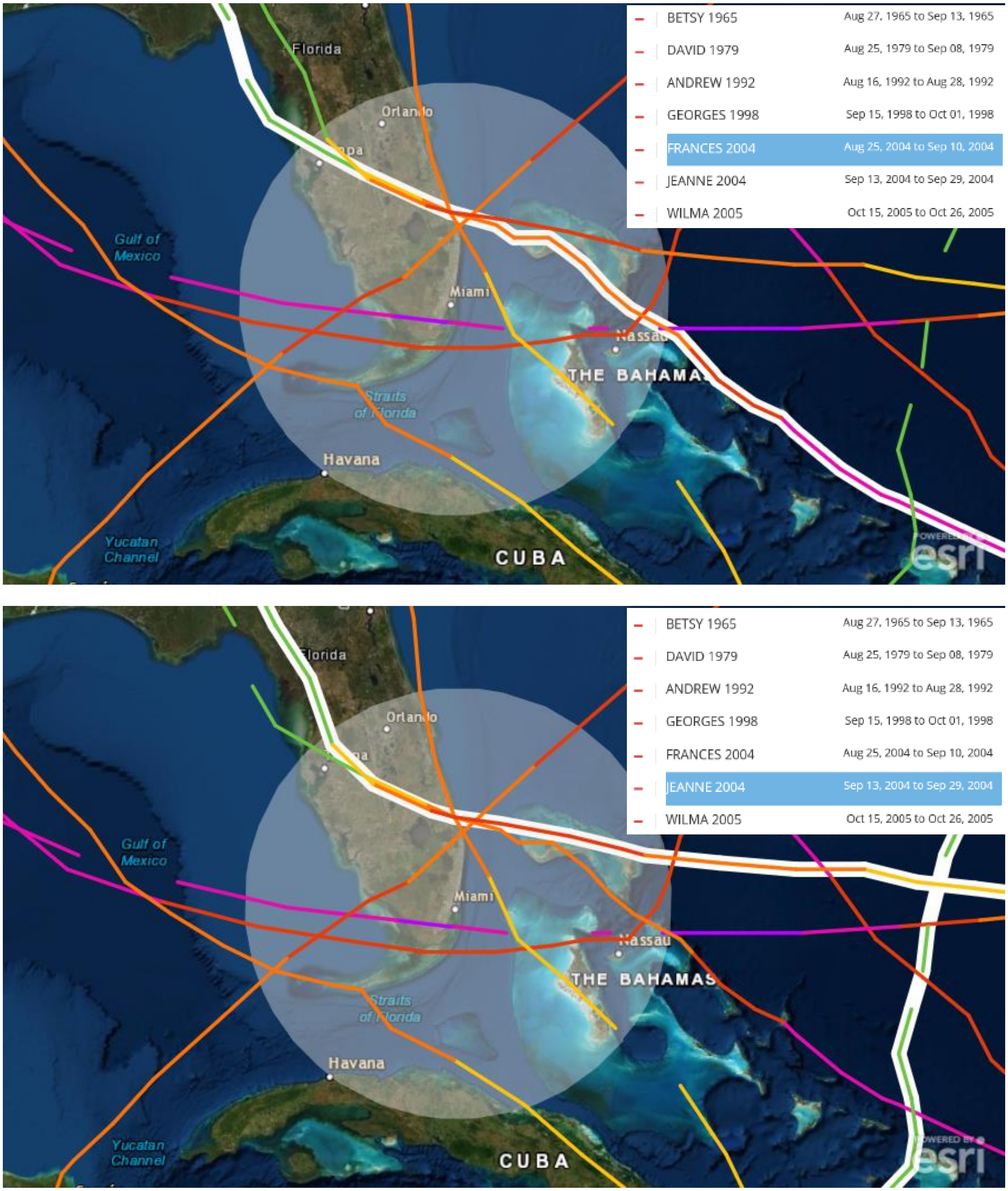


Figure 2.2: Tracks of Validation Storms compared to 2004 Hurricanes (screen capture NOAA, 2020). Hurricanes Frances (top) and Jeanne (bottom)

3. SWAN+ADCIRC Model Validation

As noted in Section 2, the SWAN+ADCIRC model requires validation to “demonstrate satisfactory model performance (waves and water levels) via comparison of model results with available measured data” [9]. FEMA reports that a “lack of measured [wave] data precludes validation of the SWAN+ADCIRC model within the study area” and relies on wave validation performed as part of FEMA’s 2014 ECCFL study among others. Thus, the model validation effort of the SFL study primarily focuses on water levels.

Two types of water level data are considered within the model validation; hydrograph data from gage measurements and highwater marks (HWM) from post-storm survey measurements. Figure 3.1 shows the locations of available water level data for the five validation storms selected by FEMA. The symbols and color scale assigned to the data locations indicate whether the modeled water elevation is above/below the measured water elevation and the magnitude of the difference between the two. It should be noted that water level data is not available at all locations for each storm.

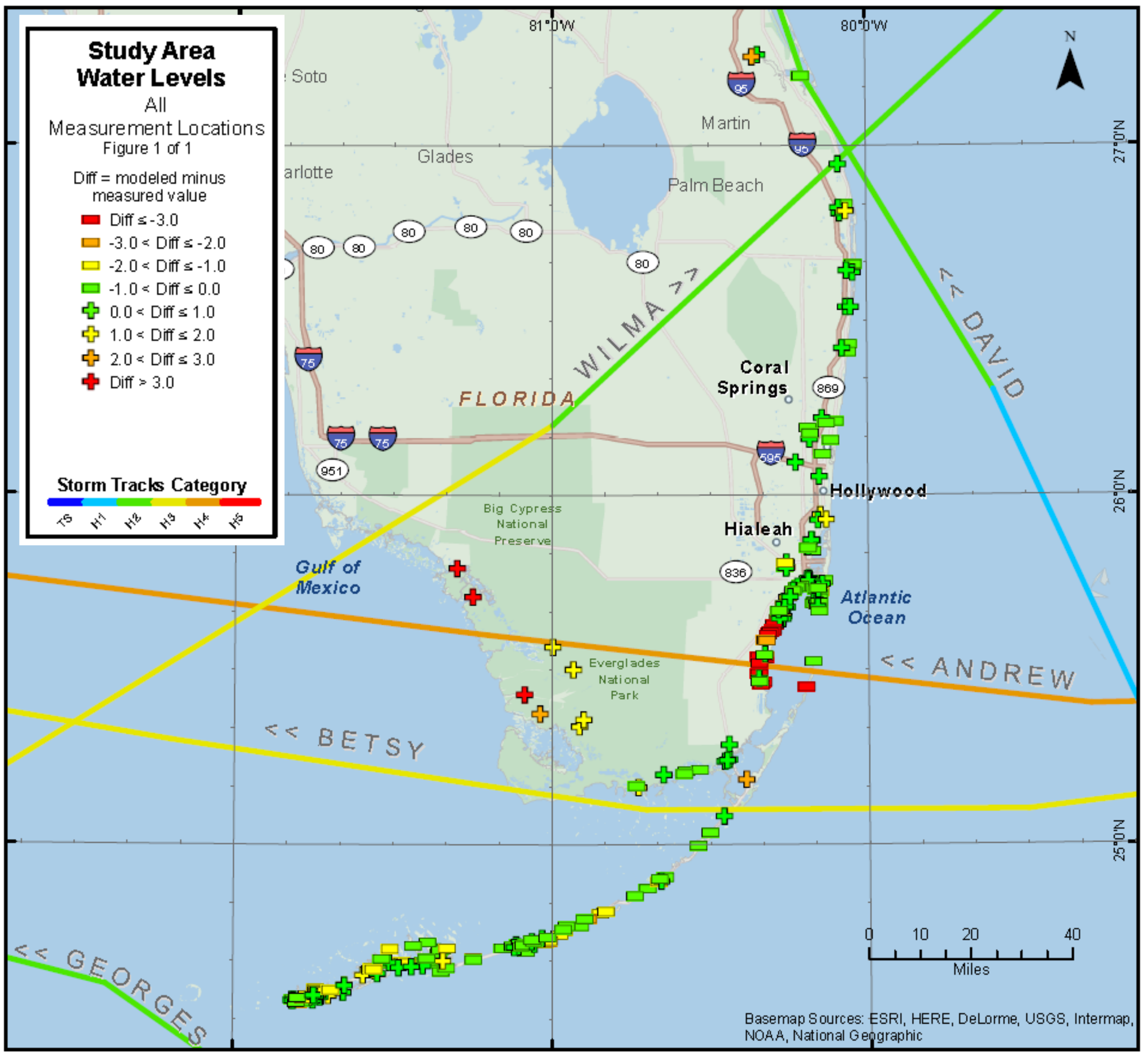


Figure 3.1: Stations with Measured HWM and Hydrograph for All Storms (FEMA, 2017; [9]).

Figure 3.2 compares modeled and measured peak water levels while providing additional detail regarding the storm and type of measurement. Solid symbols and "x" indicate peak water levels obtained from hydrographs; open symbols indicate HWM.

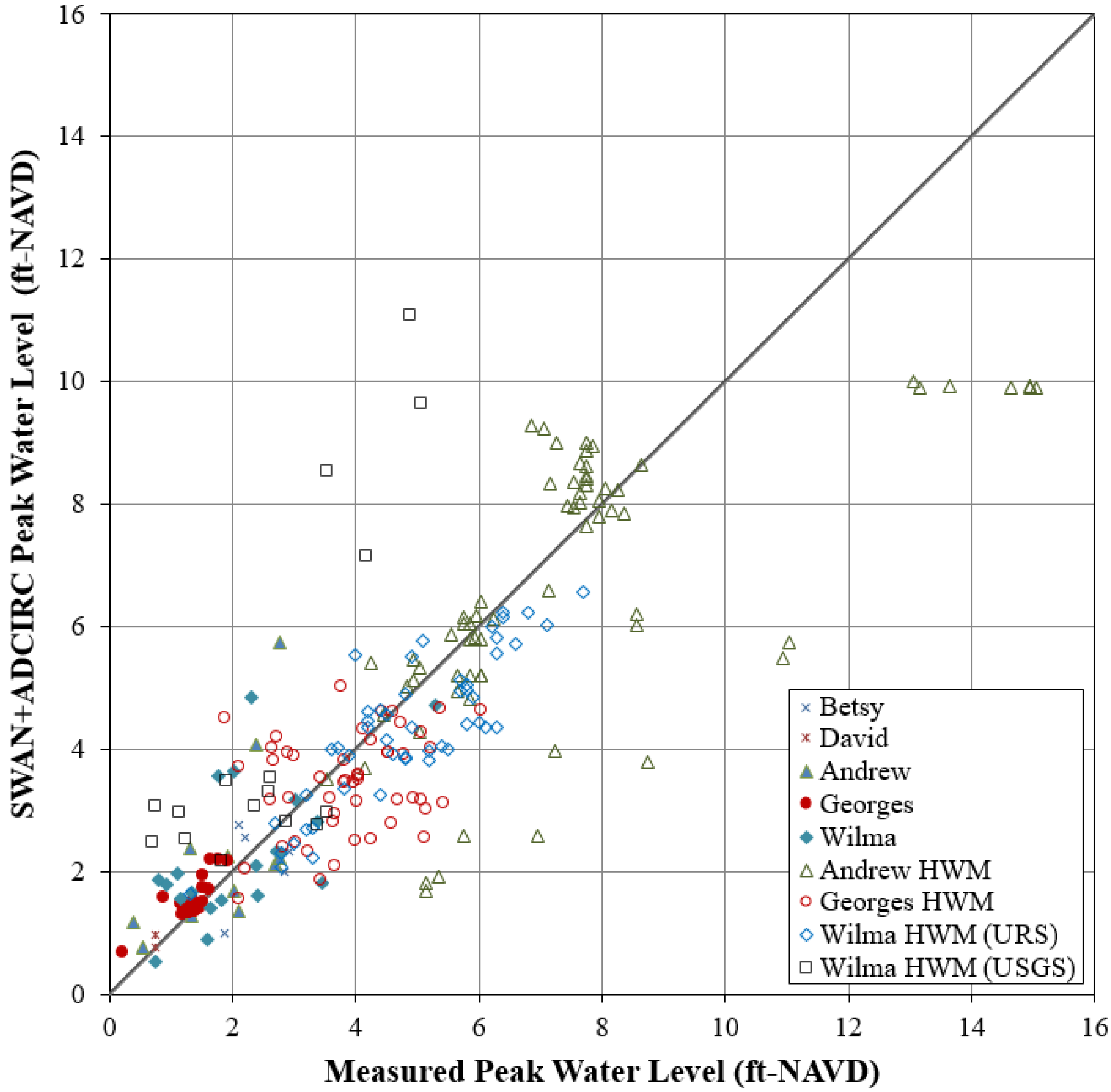


Figure 3.2: Measured-to-Modeled Peak Water Level Comparison for All Storms (FEMA, 2017; [9]).

The following observations were made from Figure 3.1 and Figure 3.2 suggesting that the proximity of measured water levels to the storm track, the gage locations, and the reliability of measured data are important to consider in the model validation.

- There was greater difference between modeled and measured water levels along the coastlines of Biscayne Bay in Miami-Dade County and Everglades National Park in Monroe County as compared to elsewhere in the study area (Figure 3.1). The modeled water levels range 2 to 3+ feet above/below the measured data. These differences are primarily associated with Hurricane Andrew in Miami-Dade County and Hurricane Wilma in Monroe County.

- The modeled water levels agree more closely with measured hydrograph data at lower water levels as compared to higher water levels (Figure 3.2). This is most evident for Hurricanes Andrew and Wilma as shown by the increased clustering of data point along the black, diagonal line at the lower left corner of the figure as compared to moving toward the upper, right corner. Lower water levels generally indicate less influence from storm surge.
- The modeled water levels agree more closely with the measured hydrograph water level data as compared to the measured HWM data (Figure 3.2). This is shown by the increased clustering of data points along the black, diagonal line for hydrograph data (solid symbols) as compared to the increased scatter for the HWM data (open symbols). This may be related to the inherent lower level of accuracy and/or lower reliability of HWM data collected manually during post-storm damage assessments as well as model uncertainty in simulating higher water levels (i.e. storm surge) where HWM are typically collected.

3.1 Proximity of Measured Water Levels to Storm Track

As storm surge decreases to zero due to distance from a storm event or as the storm tracks away from a particular location, changes in water levels are primarily governed by astronomical tides. While it is acknowledged that the extensive model validation resulted in reasonable agreement with measured astronomical tides, less favorable agreement with measured water levels during the simulated validation storm events suggests that the coastal processes associated with storm surge may not be sufficiently represented by the SWAN+ADCIRC model. This concept is highlighted by comparing hydrographs for a given location with a variety of storm tracks. Figure 3.3 shows the hydrograph for the SFWMD S44_T (DBKey 06675) gage in northern Palm Beach County with the green arrows indicating the peak water levels during Hurricanes Andrew (top), Georges (middle), and Wilma (bottom).

- The gage was located further from the storm tracks of Hurricanes Andrew and Georges and as such the influence of storm surges are expected to be less. The modeled and measured water levels are in better agreement for these storms (differences of -0.06 and 0.21 feet, respectively).
- The gage was located closer to the storm track of Hurricane Wilma. The modeled water level was overestimated 1.81 feet based on the measured data, which indicates that the model over predicted storm surge.

The model validation presented by FEMA is based on the difference between the maximum modeled and maximum measured water levels for the storm event but does not consider the timing (or phasing) of the maximum water levels during the storms. Disregard to the phase shift in the water levels can result in the misrepresentation of the model validation and thus the dynamic influence of storm surge. Figure 3.4 shows the hydrograph for the SFWMD S37A_T (DBKey 06651) gage in Broward County during Hurricane Wilma. The measured peak water level (green arrow) was 1.59 feet, NAVD88, while the modeled peak (purple arrow) was 0.88 feet, NAVD88, which resulted in a difference of -0.71 feet as reported by FEMA. The modeled water level was approximately -1 feet, NAVD88 at the time of the measured peak, which indicates a difference of approximately 2.59 feet. Differences between modeled and measured peak water levels is the basis for quantifying model bias to over- or underestimate storm surge and model uncertainty; the difference in this instance was approximately 3.5 times greater than reported. The model peak water level reported by FEMA was consistent with the high tides the 2 days prior and the day after the storm suggesting that the model simulated limited (if any) storm surge.

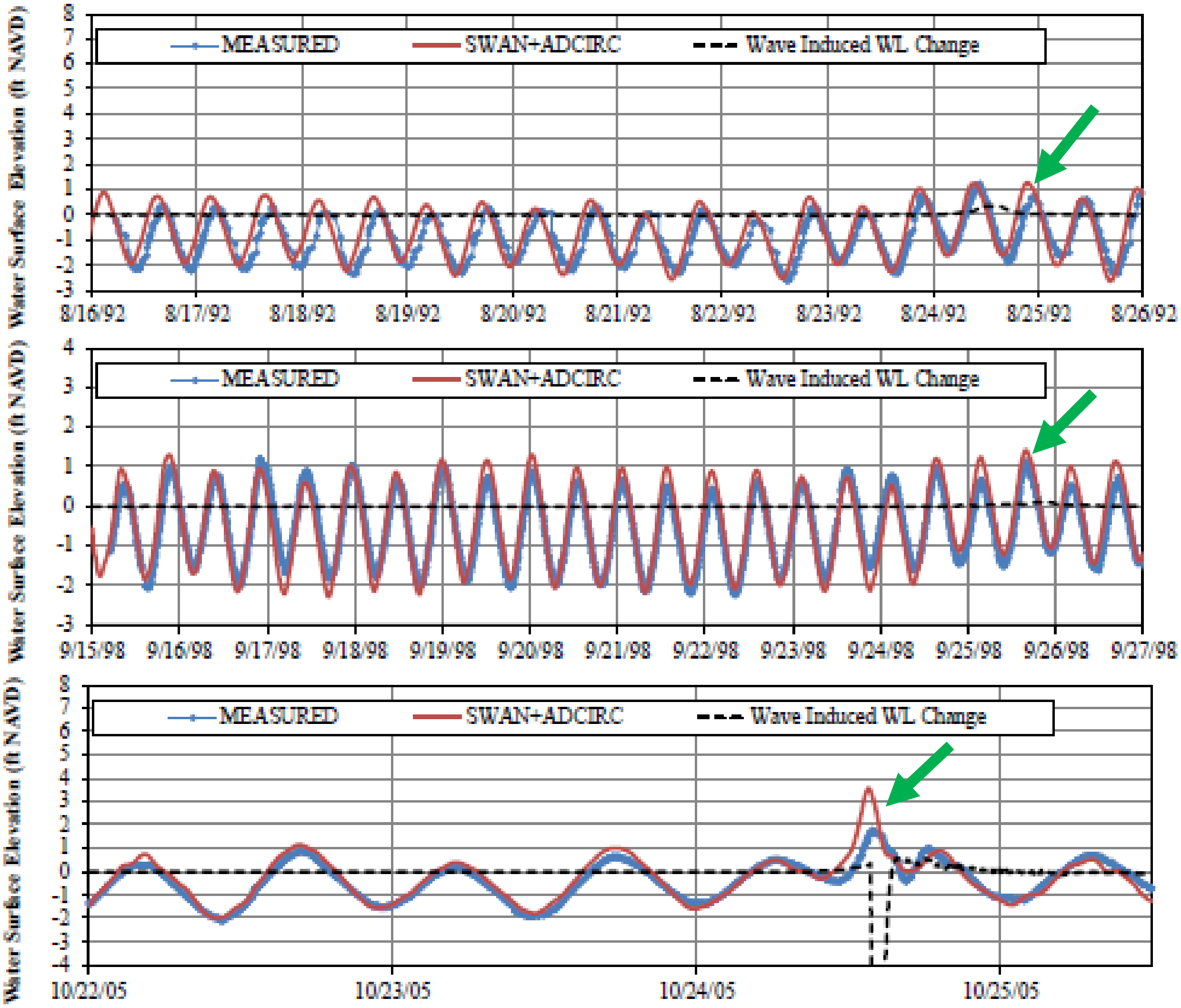


Figure 3.3: Hydrograph for Station S44_T located in northern Palm Beach County (FEMA, 2017; [9]). Hurricanes Andrew (top), Georges (middle), and Wilma (bottom).

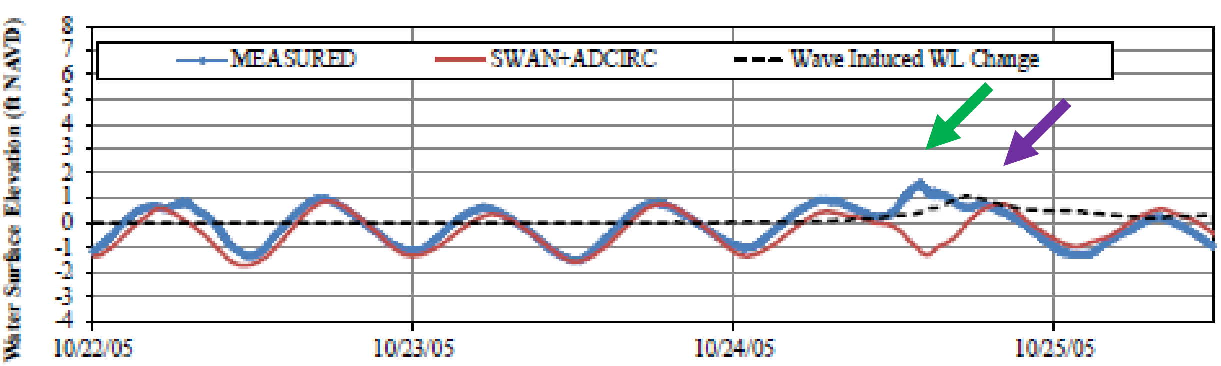


Figure 3.4: Hydrograph for Station S37A_T located in Broward County (FEMA, 2017; [9]). Hurricane Wilma.

3.2 Gage Selection

The location of the gages selected for comparison with modeled water levels can influence the model validation. Hurricane Wilma was identified as a storm for validating the SWAN+ADCIRC models for both the SFL study and the ECCFL study. The ECCFL study includes Atlantic coastline between Martin and Brevard Counties, but the model domain extended south into Palm Beach County. A comparison of the storm's peak water levels at the gages along a 60 mile segment of coastline (northern Martin County line to Highland Beach in Palm Beach County) common between the studies is shown Table 3.1. The gages are organized from north to south.

- The same gages were not included in both studies. The ECCFL study did not include gages S44_T, S155_T, and S41_T, while the SFL study did not include S46_T. Exclusion of gage S46_T is of particular importance as the gage is located within the Loxahatchee River on the oceanside of SFWMD's water control structure for the C-18 canal. The Loxahatchee River is where FEMA reported the greatest differences between the modeled 1% stillwater elevations for the ECCFL and SFL study; 2.0 to 4.2 feet [12] (see Section 4). The 1% stillwater elevation was higher for the SFL study, which suggests that the difference for Hurricane Wilma may have been greater than the 1.21 feet as reported for the ECCFL study validation at gage S46_T.
- The modeled water level was an average of 0.57 feet and 0.94 feet higher than the measured levels for the ECCFL and SFL studies, respectively. The average difference associated with the SFL study was 64% greater than the ECCFL study. An average of the differences was used by FEMA to report whether the model validation tended to over or under predict water levels (i.e. model bias). In this comparison, the positive averages indicated that the models for both studies tended to overestimate storm surge within this segment of coastline during Hurricane Wilma.
- The ECCFL study ultimately eliminated Hurricane Wilma from the model validation citing "improvement of the capability of the [model]…to reproduce non-exiting storm conditions within the project area," as well as "increased uncertainty in the wind and pressure fields for exiting storms" [12].
- Discrepancies between measured peak water elevations for the studies were noted, but was likely attributed to rounding.

Table 3.1: Hurricane Wilma Peak Water Elevations – ECCFL vs. SFL studies.

		Hurricane Wilma Peak Water Elevations (feet, NAVD88)					
		ECCFL Study			SFL Study		
Gage	County	Measured	Modeled	Difference*	Measured	Modeled	Difference*
S49_T	Martin	2.28	4.60	2.32	2.30	4.85	2.55
STL_STPT	Martin	2.33	1.93	-0.40	2.37	2.09	-0.28
S46_T	Palm Beach	0.68	1.89	1.21	-- Not Included --		
S44_T	Palm Beach	-- Not Included --			1.76	3.57	1.81
S155_T	Palm Beach	-- Not Included --			1.34	1.65	0.31
S41_T	Palm Beach	-- Not Included --			1.12	1.98	0.86
S40_T	Palm Beach	1.20	0.36	-0.84	1.16	1.56	0.40
	Average:			**0.57**			**0.94**

*Difference = Modeled - Measured

3.3 Model Uncertainty and Bias

The SWAN+ADCIRC model validation did not distinguish between the reliability of the types of measured water level data; hydrographs versus HWM. FEMA reports that model validation of storm water levels “generally consider hydrograph data superior to high water marks which record only the water level magnitude as noted and measured on structures following a storm” [9]. FEMA guidelines state that water level “gage observations are more reliable” than high water marks [18]. The model validation was based on 244 measured peak water levels (58 from hydrographs and 186 from HWM) and their differences compared to the model simulations. Model uncertainty (or model skill) is quantified as the standard deviations of the differences. The uncertainty for all 244 was 1.54 feet as reported by FEMA. The uncertainty associated with the hydrographs was 0.81 feet as compared to 1.68 feet for the HWM. This indicates that the model uncertainty was skewed by the uncertainty of the less reliable HWM, which was 2 times greater than the hydrograph uncertainty. FEMA made no adjustments during the model validation to account for the reliability of the measurement types.

Review of the model uncertainty and bias for each of the counties and with respect to the validation storms provides insight on the spatial variability of the uncertainty (see Table 3.2).

- The model uncertainty within Palm Beach County was the lowest of the four counties and 60% less than the uncertainty for the overall study area. The greatest uncertainties occurred within Miami-Dade and Monroe Counties, which were attributed to Hurricanes Andrew and Wilma, respectively.
- Hurricanes Andrew and Wilma resulted in a model uncertainty of 2.00 feet and 1.41 feet, respectively, for the SFL study. Hurricane Wilma was omitted from the model validation for the ECCFL study having had resulted in an uncertainty of approximately 1.0 foot.
- The lowest uncertainties for storms were associated with Hurricanes Betsy and David, but the validations were limited to 4-5 gages that were available for each of these storms. For each of the storms, one of the gages was NOAA’s Key West station. However, FEMA reported that the NOAA Key West gage is not suitable “to capture the maximum surge levels for storms that impact the Atlantic coastline” [4].
- Model bias was assessed by FEMA to determine whether the model validation tends to over or under predict water levels. Bias was represented by FEMA as the average of the differences between modeled and measured peak water levels. The average of the overall study area reported by FEMA was -0.25 feet, which FEMA explained as a slight model bias of under predicting water levels. Within Miami-Dade County, the average was -0.52 feet which can be largely attributed to the landfall of Hurricane Andrew in Miami. Within Palm Beach County, the average was +0.25 feet suggesting an over prediction of modeled water levels. No adjustments were made by FEMA to account for spatial variability of model bias within the study area or the influence of the apparent outlier (Miami-Dade County).

Table 3.2: Model Uncertainty and Bias.

County	Uncertainty* (feet)	Bias (feet)
Palm Beach	0.63	0.25
Broward	0.64	0.05
Miami-Dade	1.84	-0.52
Monroe	1.36	-0.15
Overall	1.54	-0.25

Validation Storm	Uncertainty* (feet)	Bais (feet)
Betsy (1965)	0.72	-0.26
David (1979)	0.13	0.07
Andrew (1992)	2.00	-0.65
Georges (1998)	0.99	-0.24
Wilma (2005)	1.41	0.09
Overall	1.54	-0.25

*Uncertainty = model skill

4. Statistical SWEL

Following validation, the SWAN+ADCIRC model was used to simulate water surface elevations throughout the study area during 392 synthetic storms that were selected by FEMA using the Joint Probability Method – Optimal Sampling (JPM-OS) approach. At each model node for each storm, the maximum water surface elevation (WSE) was recorded along with recurrence interval of the storm. This information along with the model uncertainty estimated during model validation (see Section 3) were used as inputs to the SURGE_STAT program, which generated the statistical stillwater elevations (SWEL) for each node within the SWAN+ADCIRC model domain. A major contribution in identifying FEMA's special flood hazard areas (SFHA) was the 1% SWEL. Thus, considerations with respect to the development of the 1% SWEL are presented below.

4.1 JPM-OS Approach and Assumptions

The Joint Probability Method (JPM) with Optimal Sampling (OS) is a well-established, widely applied and standardized mathematical approach for the estimation of low frequency storm surge elevations in regions impacted by hurricanes. The JPM-OS method was applied to the SFL study and is cited as FEMA's preferred method based on the agency's 1988 publication on Coastal Flooding Hurricane Storm Surge Model [10]. The following approaches and assumptions presented in the JPM-OS report [10] warrant further consideration regarding their appropriateness in accurately estimating storm surge within the study area.

- New advances in methodology for describing long duration hurricane climatology and joint probability for estimation of low probability inundation are now routinely applied. For example, stochastic Monte Carlo modelling approaches whereby synthetic track sets based on historical hurricane climatology that capture the full randomness and variability in hurricane track paths and intensity/scale characteristics are now routinely applied for storm surge studies around the globe. FEMA applied a Monte Carlo approach for a coastal study in North Carolina (2008) and approved use of this method in FEMA Guidance No. 8-12 (2012). The SFL study utilized a Monte Carlo approach in accounting for tides within the study area to "provide more efficient solutions for problems that have high dimensionalities" [10]. Justification was not provided for the combination of JPM-OS and Monte Carlo approaches for storm surge and tides, respectively, as opposed to a single more advanced approach.
- FEMA reported that storm forward speed is considered of less importance as compared to a storm's pressure and radius based on FEMA's Mississippi coastal study in 2008. As such, the probability distribution for forward speed was less discretized (i.e. more coarsely resolved) as compared to other storm parameters. The profile of the continental shelf may affect the relative "importance" of storm parameters within the model. The Gulf coast of the study area has a wider, shallower, and flatter shelf that has greater similarity to the Mississippi coast as compared to the Atlantic coast with a narrower, deeper, and steeper shelf. The relative importance of the parameters to and within the SFL study area was not demonstrated, rather was pre-assumed. FEMA noted challenges during the model validation for Hurricane Andrew on the Atlantic coast, which were presumed related to wind field asymmetry and storm track but never resolved (see Section 2). The pre-assumed "importance" of parameters appears to have justified the use of a symmetric wind field for the Holland B parameter, which may have inaccurately accounted for wind field asymmetry due to a storm's forward speed and its interaction with the narrower, steeper Atlantic continental shelf.
- The JPM-OS approach assumed statistical stationarity across the study area. While this may be a reasonable assumption given the relative short duration of observed data compared to the number of low frequency events, differences in the adopted distributions applied to adjacent study areas (e.g. ECCFL study) will result in discontinuities at the boundaries of the study (see Section 4.4).
- FEMA reported that the ADCIRC model was employed for several reasons, one of which was the model "can simulate the momentum [interactions] associated with tidal conditions" [12] and storm surge. An

example of the effect of momentum interactions is that the inland extent of flood may reduce when storm surge arrives at a coast during the period of a falling tide. The dynamic modeling of tides and storm surge was not considered by FEMA in defining the synthetic storms to represent the optimized storm set, but rather only included during the modeling of the optimized storm set itself.

- The Gulf and Atlantic coastlines within the study area face nearly opposite directions. As such, FEMA performed separate JPM-OS analyses for the two coasts and allowed the SWAN+ADCIRC model parameters to be adjusted to reflect the coastal processes unique to the coasts improving model validation. Thus, landfalling storms were modeled using different SWAN+ADCIRC parameters as compared to exiting storms for the same coast. This approach was different from the approaches for the ECCFL and Southwest Florida (SWFL) coastal studies, where landfalling and exiting storms were modeled within a single JPM-OS analysis. The effects of this approach on the model validation was not documented by FEMA and warrants additional analysis to quantify its effects on the 1% SWEL.
- The meteorological optimization evaluated the influence of the synthetic storms on the 1% SWEL and removed storms that did not significantly contribute to the 1% SWEL. The optimization evaluated storm surge by assuming a constant mean sea level (i.e. tides were not included). Subsequently, a tidal optimization was completed using a Monte Carlo approach to randomly assign a start date to the remaining synthetic storms. The tidal optimization accounted for the timing of storms with respect to the tide cycle (e.g. high and low tides). The meteorological optimization did not account for the momentum interactions of storm surge and tide in initially screening the storms, and the tidal optimization may have potentially resulted in under sampling the more extreme storms contributing to the 1% SWEL. Under sampling of the extreme storms can cause the "tail" of the statistical distribution of the extremal analysis to steepen, thereby overpredicting water levels (i.e. higher water levels) for low frequency storm events (see Section 4.3).
- The dates for FEMA's tidal optimization were based on a selected 3-month period during the peak of the Atlantic hurricane season (August to October). The 3-month period during 2015 was identified by comparing the tide histogram over the long-term between 1985 and 2015 at several locations. Inspection of the tidal range histograms suggests that the 2015 period may have overrepresented the larger tidal ranges at each of the locations, which contributes to the 1% SWEL defined by FEMA. The histogram presented by FEMA at the Lake Worth Pier is shown in Figure 4.1; the overestimated larger tides for the 2015 period increased the mean tide range approximately 0.10 feet as compared to the long-term period.

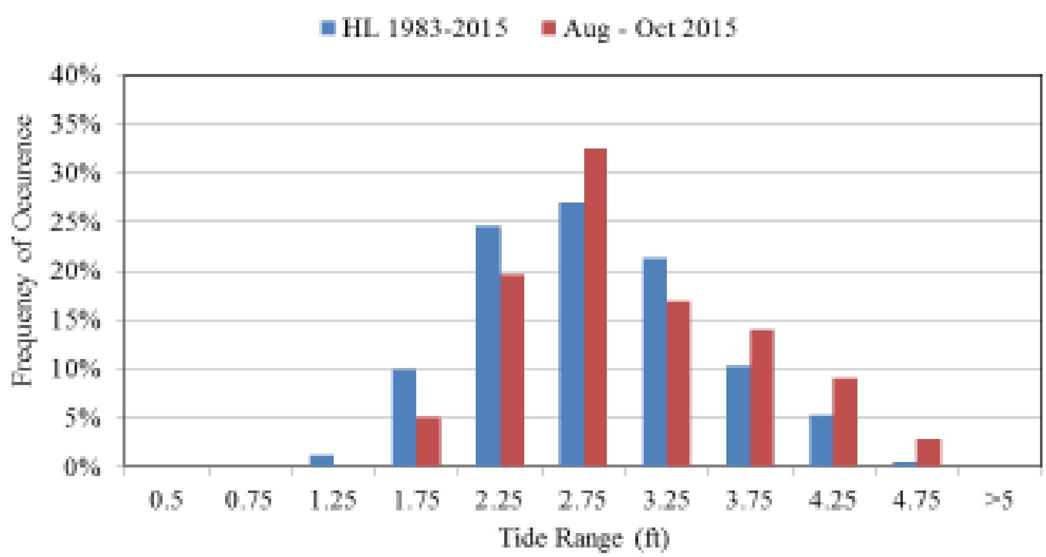


Figure 4.1: Tidal Range Histogram – Lake Worth Pier (FEMA, 2016; [10]).

4.2 Model Mesh

The SWAN+ADCIRC model requires that model grids (meshes) be developed to define bathymetric/topographic elevations as well as to define storm forcing parameters (e.g. winds and pressure fields) throughout the study area. FEMA states "for each new SWAN+ADCIRC model mesh, validation must demonstrate satisfactory model performance" [2]. FEMA's evaluation of model performance for the SFL study focused on water surface elevations (e.g. 1% SWEL).

FEMA's mesh for defining bathymetric and topographic features had a coarser resolution offshore and a finer resolution onshore (Figure 4.2). Finer mesh (close nodal spacing) is required to more accurately describe inland water bodies, channels, canals, and land/water interfaces. FEMA reported that along the Intracoastal Waterway (ICW) and adjacent canal systems, the mesh "included channels at least 30-feet wide…such that at least one element spanning the channel remains wet when the water level lies at or above low tide level" [8], while channels narrower than 30 feet were excluded.

Based on initial review of 1% SWEL as reported by FEMA (Figure 4.3), the following locations within Palm Beach County were identified as areas that may warrant further consideration with respect to the developed model mesh. The buildup of water, and equally the exchange of water, may be the result of the coastal processes below, but FEMA's model mesh will need to be reviewed in greater detail.

- <u>Southern Lake Worth Lagoon</u>: The highest 1% SWEL values were simulated within the southern portion of the Lake Worth Lagoon immediately interior of South Lake Worth Inlet (a.k.a. Boynton Inlet). This may be attributed to the exchange of water through the inlet, northerly winds (likely during landfalling hurricanes) forcing water within the lagoon south to the constriction of the ICW, or a combination thereof.
- <u>Northern Lake Worth Lagoon</u>: The next highest 1% SWEL values occur at the northern portion of the lagoon. Lake Worth Inlet (a.k.a. Palm Beach Inlet) is located further away as compared to the situation at the southern portion of the lagoon, but the inlet is wider and deeper improving its ability to exchange water with the Atlantic Ocean. Southerly winds (likely during exiting hurricanes and after the passing of landfalling hurricanes) forces water into the constricted ICW and tributary canals.
- <u>Loxahatchee River</u>: The river's major tidal connection is through Jupiter Inlet, with some influence from the narrow ICW to the north and south. FEMA reported that the greatest discrepancy (ranging from 2.0 to 4.2 feet) between 1% SWELs for the SFL and ECCFL studies occurred within the river (see Section 4.4).

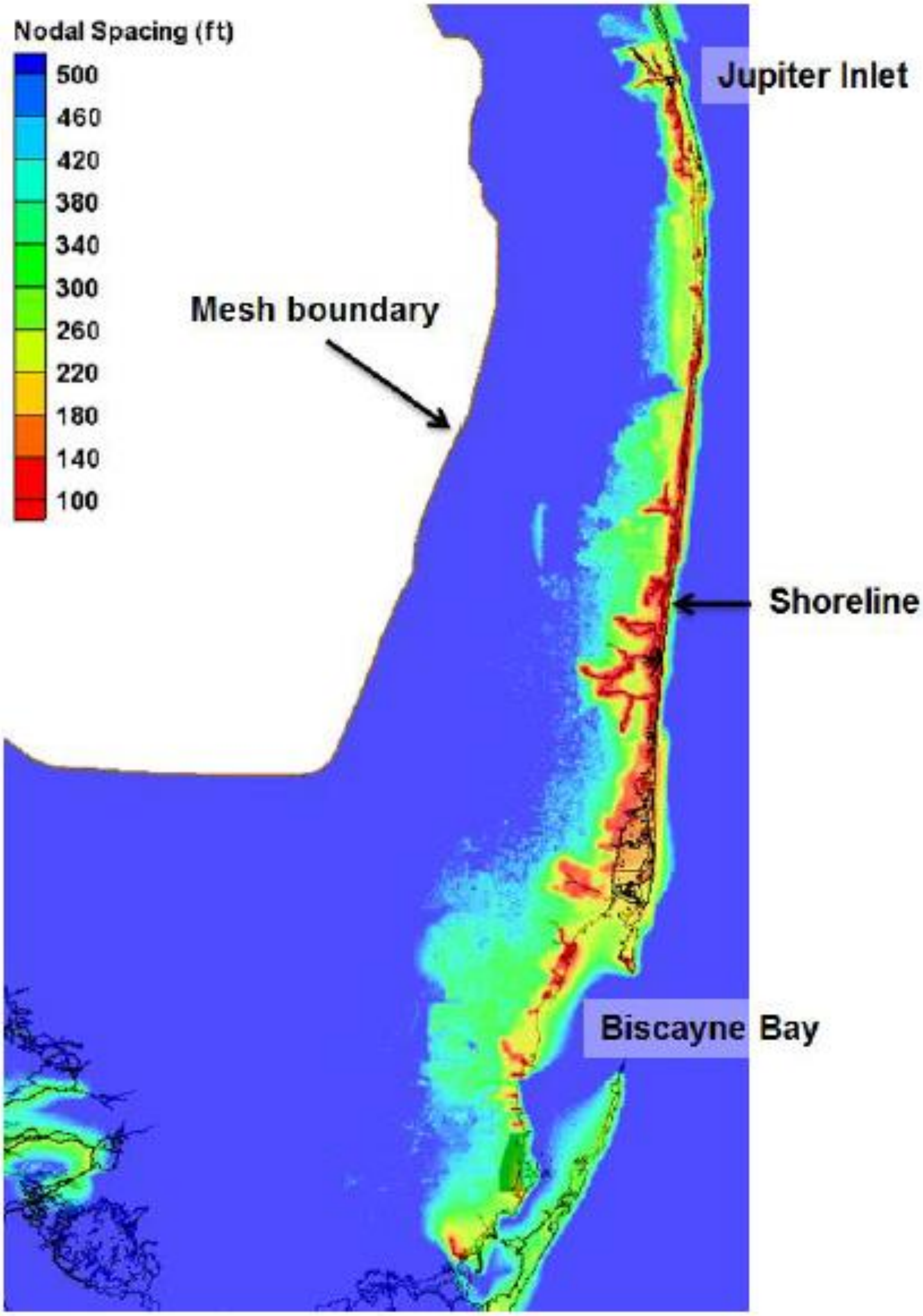


Figure 4.2: SWAN+ADCIRC Model Mesh – Nodal Spacing (FEMA, 2016; [8]).

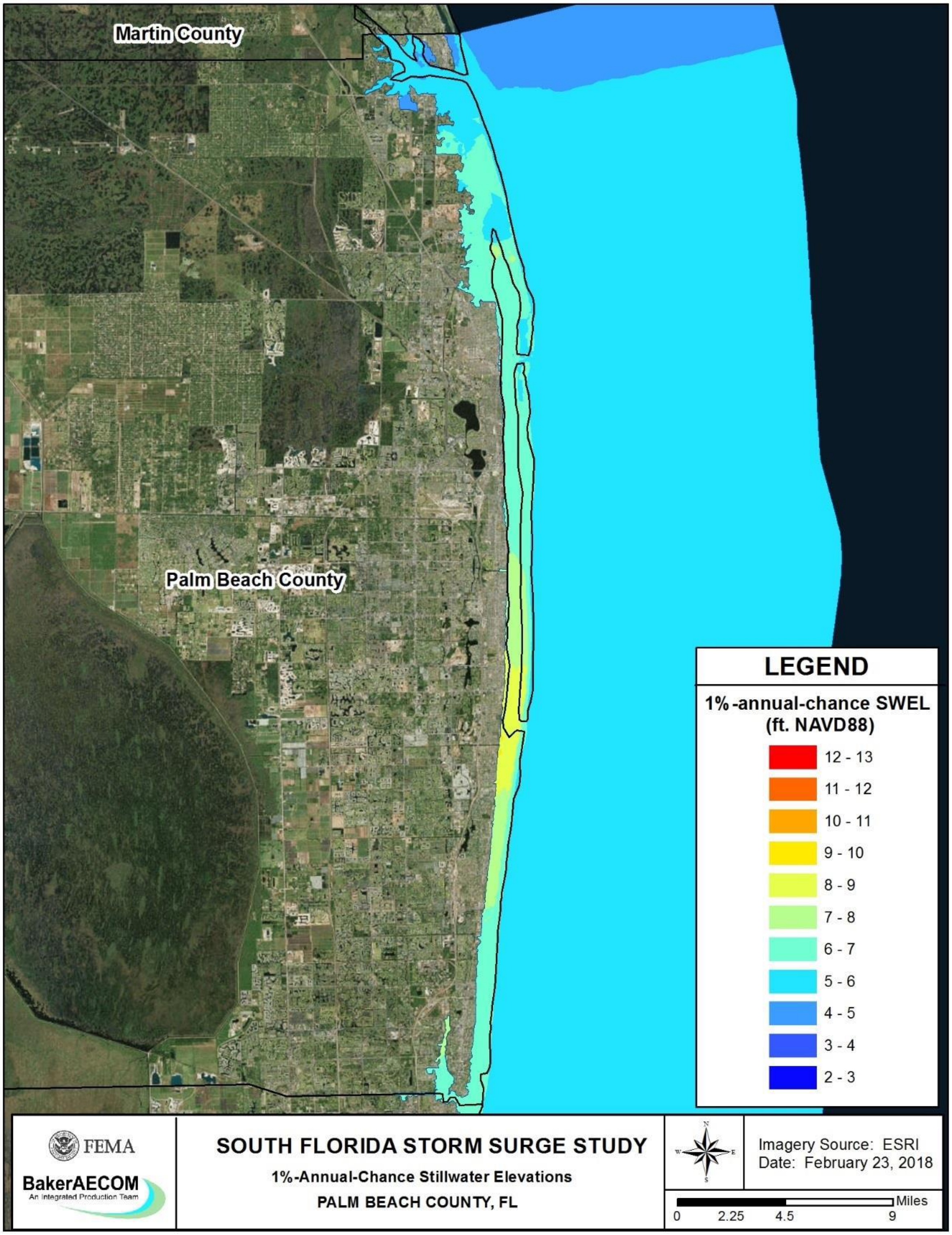


Figure 4.3: 1% SWEL – Palm Beach County (FEMA, 2018; [12]).

4.3 1% SWEL

The 1% SWEL is considered by FEMA as the major factor to define the inland extent of coastal special flood hazard areas (SFHA) when overlaid on digital elevation models (DEM). The water surface elevation (WSE) for each synthetic storm within the optimal sampling dataset is recorded at each of the nodes within the model mesh. The maximum WSE and model uncertainties are used as inputs to the SURGE_STAT program that generates return frequency curves at each model node.

The total model uncertainty is comprised of two terms; model skill and the planetary boundary layer terms. A larger model uncertainty results in return frequency curves that yield higher 1% SWEL.

- Model Skill term "represents the variations in water surface elevations due to lack of modeling accuracy as a result of approximations in physical processes" [12]. This term is reflected by the model uncertainty presented in Section 3.3. The model skill term was estimated at 1.54 feet and was applied uniformly throughout the modeling domain which includes Palm Beach County, along with Broward, Miami-Dade, and Monroe Counties. No distinction was made to account for the potential spatial variability within the study area.
- Planetary Boundary Layer (PBL) term "represents the variations in water surface elevations due to a range of departures from the real behavior of hurricane wind and pressure fields that are not well represented by the planetary boundary layer" [12]. FEMA assumed a PBL term of 1.17 feet based on FEMA's Mississippi coastal study in 2008 for which the same wind and pressure field methodologies and sources for data generation were applied. FEMA reported "increased uncertainty in the wind and pressure fields for exiting storms" [12], which suggests that FEMA's assumption may not have been applicable and that revaluation of the PBL term may have been warranted for the SFL study.

The SURGE_STAT program was utilized to define the 1% SWEL at each model node, but it was not until FEMA began its coastal hazard analysis (see Section 5) that potential issues were identified. The hazard analysis requires the 1% SWEL as well as the accompanying wave heights and periods associated with the 1% event. FEMA's methodology to define the wave parameters is to identify the synthetic storm with a WSE closest to the 1% SWEL and nine storms above and nine storms below the 1% SWEL. The wave parameters at the storms' peak water levels are then averaged. When FEMA's methodology was applied, the 1% SWEL were above the maximum WSE of the individual storms at model nodes which FEMA attributed to the model "uncertainty term and the combined storm frequency curves" in defining the 1% SWEL [14]. FEMA's methodology to define the wave parameters for the coastal hazard analysis was modified to reduce the number of storms included in the average, but no refinements were made to resolve the actual 1% SWEL throughout the study area. This indicates that the 1% SWEL may have been overestimated and was not sufficiently bracketed by the synthetic storms, which may have also been a relic of under sampling of the extreme events as part of the JPM-OS approach (see Section 4.1). Furthermore, FEMA reported that model nodes "in some areas" were affected by the situation but limited (if any) information was provided regarding the locations or spatial extents of the affected nodes.

4.4 SWEL Transition Areas and Adjustments

FEMA states that "having matching water levels across study area boundaries is considered desirable, so that the communities on either side of the boundary do not have widely differing base flood elevations" [12]. Base flood elevations are directly affected by the 1% SWEL and as such transition areas are sometimes incorporated in the 1% SWEL to achieve agreement between studies. FEMA states that "differences of 1 foot in magnitude at storm surge study boundaries are within typical range" and "are the result of differences in the model frameworks and model parameterizations" [12]. Differences at the boundaries of other FEMA coastal studies and FEMA's respective transition areas are described below for context.

- The northern boundary on the Gulf coast of the SFL study abuts with the southern boundary of the Southwest Florida (SWFL) coastal study. This occurs at the Monroe and Collier county lines. At the boundary, the 1% SWEL for the SFL study were approximately 1.0 feet higher at the coastline and 0.5 feet higher inland as compared to the SWFL study. A narrow transition area was identified and the SFL study 1% SWEL were adjusted down to agree with the SWFL study.
- The northern boundary on the Atlantic coast for the SFL study abuts with the southern boundary of the ECCFL study. This occurs at the Palm Beach and Martin county lines. At the boundary, the 1% SWEL for the SFL study were higher by "1.7 feet along the open coast, 2.0 feet in the Intracoastal Waterway, and 2.0 to 4.2 feet up the Loxahatchee and North Fork Loxahatchee Rivers" [12] as compared to the ECCFL study. A 10-mile wide transition area was identified extending 5 miles north and south of the county line within which the SFL study 1% SWEL were adjusted down and the ECCFL study was adjusted up to achieve agreement.
- The northern boundary of the ECCFL study abuts with the southern boundary of the Georgia-Northeast Florida (GANEFL) coastal study. This occurs at the Brevard and Volusia county lines. At the boundary, the 1% SWEL for the ECCFL study were higher by 2.0 feet along the open coast and less than or equal to 0.5 feet in the Mosquito Lagoon as compared to the GANEFL study. An approximately 25-mile wide transition area was identified extending approximately 12 miles north and south of the county line within which the ECCFL study 1% SWEL were adjusted down to agree with the GANEFL study.

Justification for defining the 10-mile wide SFL study transition area was not provided by FEMA. The following presents a basis for redefining the transition area applied between the SFL and ECCFL studies that aligns with other FEMA studies.

- The differences at the study area boundary between the SFL and ECCFL studies were comparable on the open coast and 4 times larger within the Intracoastal Waterway (ICW) as compared to the differences reported at the northern boundary of the ECCFL study.
- The smaller adjustments at the northern boundary of the ECCFL were applied to the southern half (12 miles) of the 25-mile wide transition area. The transition area was defined to align with the limits of the Canaveral National Seashore.
- Assuming that the width of the SFL study transition area should be scaled to achieve a similar linear adjustment within the ICW as the ECCFL, the SFL transition area should have a redefined alongshore length of 48 miles, which is much greater than the 10-mile wide transition area used by FEMA. Assuming that the transition area is shifted south to align with the redefined adjustments applied within Palm Beach County as described below, the northern limit of the transition area would be approximately 3 miles north of the Palm Beach and extend south to include all of Palm Beach County (Figure 4.4).

FEMA presented a detailed discussion explaining the factors that contributed to the differences between the 1% SWEL for the SFL and ECCFL studies [12]. FEMA's discussion did not explicitly state which water body was being analyzed, but it could be inferred that the discussion could be applicable to the open coast given the relatively close agreement of the values discussed. FEMA explained that differences in the SWELs were attributed to model uncertainty (0.80 feet), interpolation techniques in estimating mean sea level (MSL; 0.30

feet), and the inclusion of west coast (exiting) storms in the SFL study (0.25 feet). FEMA's explanation did not explicitly assign the differences to each of the studies nor did the summation of absolute adjustments equal any of the differences identified.

Review of FEMA's reports for the ECCFL study revealed that FEMA excluded west coast (exiting) storms from both the model validation for ECCFL study as well as the JPM-OS modeling. FEMA's explanation was that "exiting storms have a minimal effect on the low-frequency water levels" and "the presence of other uncertainties which influence the modeling results to a larger degree." The ECCFL study documented that inclusion of exiting storms increased the 1% SWEL by 0.08 feet. FEMA reported that the influence of west coast storms on the SFL study was 0.25 feet (3 times greater than the ECCFL study) but FEMA opted to include them regardless.

In the absence of re-performing the SWAN+ADCIRC modeling to explicitly resolve the differences noted by FEMA, the following presents a basis for more clearly redefining adjustments to the 1% SWEL by assigning differences to the respective FEMA studies (Table 4.1).

- The storm surge bias estimated within Palm Beach County (see Section 3.3) and the overestimated tidal optimization (see Section 4.1) were included to achieve agreement with the 1.70 feet difference along the open coast.
- This resulted in a 1.40 feet reduction in the 1% SWEL within the SFL study and an increase of 0.30 feet within the ECCFL study; as compared to FEMA's assumed even distribution of 0.85 feet reduction and 0.85 feet increase for the SFL and ECCFL studies, respectively.
- As such, there is a strong justification that at least 82% (40 miles) of the proposed redefined 48-mile transition area for the open coast and ICW be located within Palm Beach County. This redefined transition area would be located to include the entirety of Palm Beach County's 45-mile coastline and extend 3 miles north into Martin County (Figure 4.4).
- The redefined adjustments and transition area were based on values reported by FEMA. Additional analysis of the modeling may result in revisions to the refinements presented herein.

Table 4.1: 1% SWEL Adjustments along the Open Atlantic Coast.

	1% SWEL Adjustments along Open Coast (feet)			
	FEMA		Redefined	
Factor	ECCFL Study	SFL Study	ECCFL Study	SFL Study
As Explained				
Model Uncertainty		-0.80		-0.80
MSL	0.30		0.30	
West Coast Storms		-0.25		-0.25
Storm Surge Bias				-0.25
Tidal Optimization				-0.10
Adjustment as Assigned	0.30	-1.05	0.30	-1.40
Absolute Adjustment		1.35		1.70
Proportion of Adjustment	22%	78%	18%	82%
As Applied				
Application of Adjustments	0.85	-0.85	0.30	-1.40
Absolute Adjustment		1.70		1.70
Proportion of Adjustment	50%	50%	18%	82%

Figure 4.4: Redefined SFL and ECCFL Transition Area.

5. Coastal Hazard Analysis

The coastal hazard analysis considers processes governing the open coast and sheltered waters during extreme storm events at defined cross-shore transects. The open coast includes the Atlantic coastline within Palm Beach County; sheltered waters are associated with inland water bodies (e.g. Intracoastal Waterway, Loxahatchee River, and Lake Worth Lagoon). Transect location maps are provided in Appendix A.

5.1 Open Coast

The analysis along the open coast evaluates coastal erosion, wave runup, and overtopping. The SFL study analyzed 170 transects within Palm Beach County for each of the coastal processes to map the VE Zone. The analysis is summarized below [17].

- Coastal erosion was evaluated in terms of the dune response to a storm event; dune retreat or dune removal. The dune response was evaluated based on the volume of the dune “reservoir” seaward of the dunes landward crest and above the 1% SWEL. A dune reservoir greater than 540 square feet were assumed to retreat (erode), while dune reservoirs less than this amount were assumed to be removed. Eroded dune profiles were “constructed” based a FEMA’s defined methodology. Changes to the 1% SWEL (see Section 4) may affect FEMA’s evaluation of dune response and in turn mapping of flood zones. Additional review of the Wave Height Analysis for Flood Insurance Studies (WHAFIS) modeling and input parameters regarding the landward limit of the dune crest and “construction” of the eroded profiles may be warranted.
- The WHAFIS model was used to propagate the offshore wave conditions from outside the surf zone to the beach. The offshore wave conditions (wave height and period) associated with the 1% SWEL storm event were obtained from the SWAN+ADCIRC modeling (see Section 4.3). FEMA’s analysis assumed that the direction of wave propagation was shore normal (perpendicular to shore), which is a requirement of the WHAFIS model as it does not account for wave refraction due to bottom interactions. Furthermore, FEMA analysis assumed that the peak wave height coincided with the peak water surface elevation. While not necessarily an incorrect assumption, FEMA did not provide justification for these assumptions and if inappropriate can result in an overestimation of the wave conditions (e.g. wave heights) at the beach.
- Based on the wave conditions at the beach, wave runup was analyzed using the RUNUP2.0 model, USACE Shore Protection Manual (SPM) or Technical Advisory Committee for Water Retaining Structures (TAW) methods. Coastal structures (e.g. seawalls) were identified and assumed to fail within Palm Beach County as FEMA reported that none of the structures were certified to withstand the 1% storm event.
- If the wave runup was identified to extend above a coastal structure or eroded dune profile, then wave overtopping and breaking wave heights were evaluated.
- FEMA defines the primary frontal dune (PFD) as the “continuous or nearly continuous mound or ridge of sand with relatively steep seaward and landward slopes immediately landward and adjacent to the beach and subject to erosion and overtopping from high tides and wave during major coastal storms. The inland limit of the primary frontal dune occurs at the point where there is a distinct change from a relatively steep slope to a relatively mild slope” [17]. FEMA guidance defines the area extending from offshore to the inland limit of the PFD along an open coast as a coastal high hazard area. Coastal high hazard areas are defined as a FEMA VE zone, which are at greater flood risk during coastal storms.
- FEMA guidance requires that the VE zone along the open coast be mapped according to the wave runup, wave overtopping, breaking wave height, or the PFD, whichever is most landward. Consistent mapping of the PFD, which is more often the most landward parameter, is important to consistently defining flood risks within the study area (e.g. barrier islands of Palm Beach County).

FEMA delineated the landward limit of PFD for the SFL study based on site reconnaissance and review of topographic surveys. Delineation of the PFD was reviewed for appropriateness and to confirm consistency throughout Palm Beach County. Inspection of FEMA's transects suggested that the PFD delineation was not consistent throughout the County in that the PFD limit was located further seaward relative to the beach profile in the southern portions of the County as compared to the northern portions. Lake Worth Inlet was identified as the demarcation where the mapping inconsistency occurred. Of the 170 open coast transects within the County, 123 were located south of the inlet and 47 to the north (Table 5.1). The PFD was delineated for 75% of the transects south of the inlet as compared to 98% to the north; the difference was attributed to the greater number of coastal structures (e.g. seawalls and revetments) south of the inlet. The more seaward delineation of the PFD south of the inlet is evident by the PFD being the defining the limit of the VE zone on 44% of the transects south of the inlet as compared to 87% to the north.

Example transects depicting the inconsistent PFD delineations south and north of the inlet are shown in Figure 5.1 and Figure 5.2, respectively. The pink dots in the figures represent FEMA's PFD locations. The PFD locations are seaward of the highest portion of the beach profiles (15-20 feet, NAVD88) south of the inlet (Figure 5.1), while they are located landward of the beach profiles' high point north of the inlet (Figure 5.2). Additional details regarding the open coast transects are provided in Appendix B.

Table 5.1: Primary Frontal Dune Analysis.

Coastline (Open Coast Transects)	# of Transects			% of Transects	
	Open Coast	PFD Delineated	VE Zone Defined by PFD	PFD Delineated	VE Zone Defined by PFD
South of Lake Worth Inlet (1 to 123)	123	92	54	75%	44%
North of Lake Worth Inlet (124 to 170)	47	46	41	98%	87%
Palm Beach County (1 to 170)	170	138	95	81%	56%

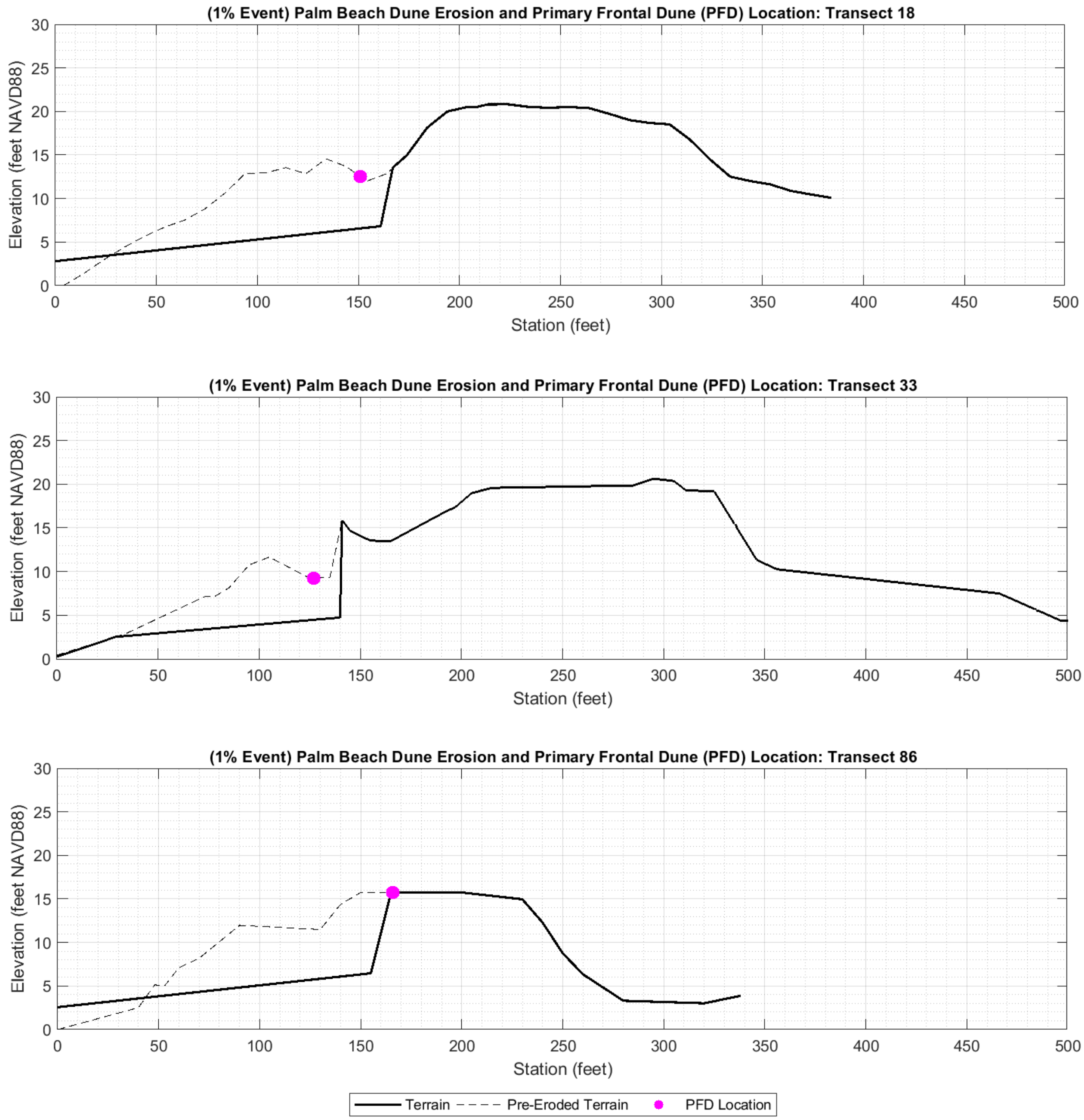


Figure 5.1: PFD - Transects 18, 33 and 86 South of Lake Worth Inlet (FEMA, 2019; [15]).

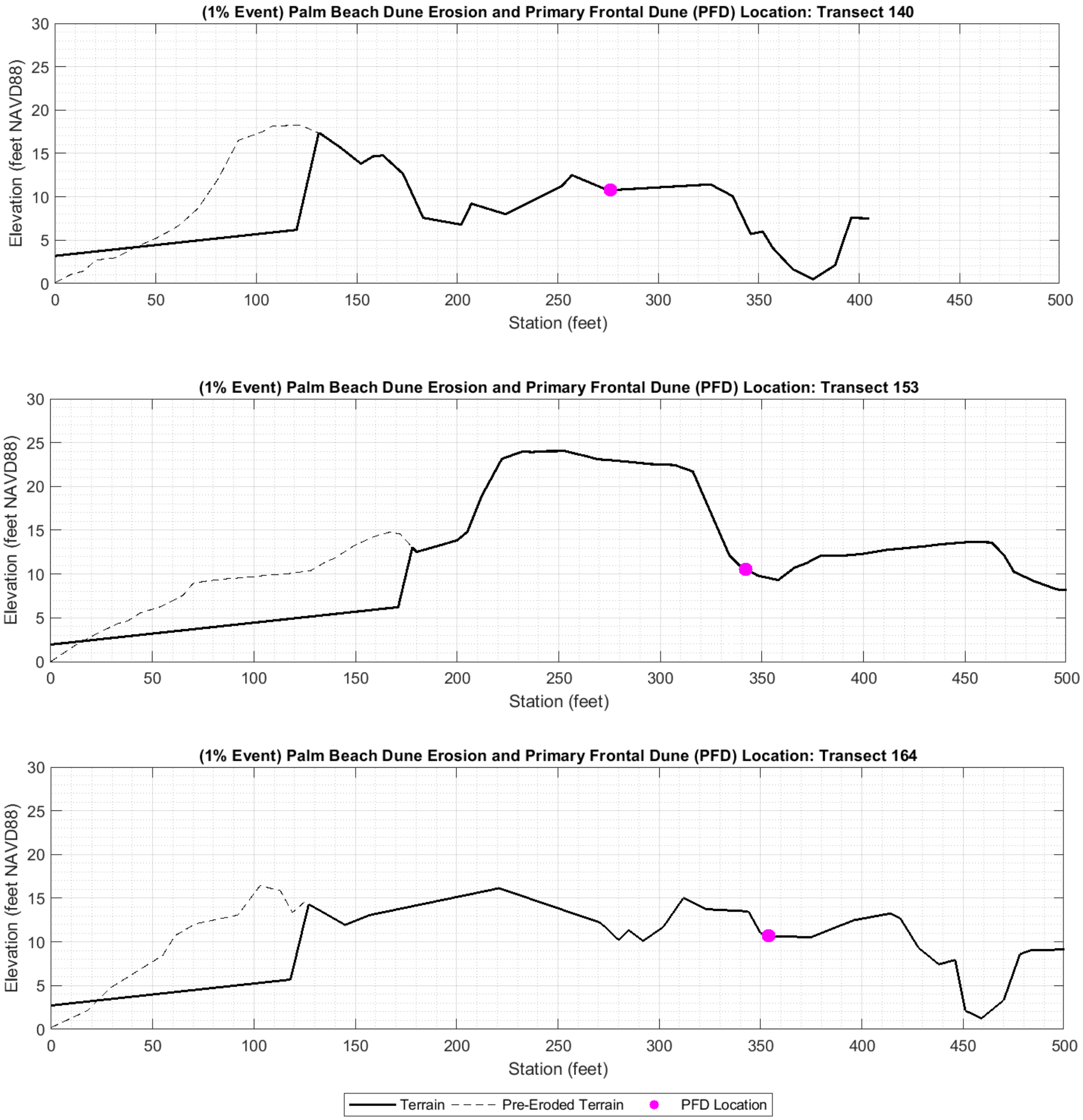


Figure 5.2: PFD - Transects 140, 153, and 164 North of Lake Worth Inlet (FEMA, 2019; [15]).

Based on review of the transects, the following was noted, which may require further consideration by FEMA in addition to a more consistent mapping of the PFD. Concepts presented below may have occurred at other transects in addition to those discussed herein.

- Transect 134: FEMA identified that dune removal would occur at the transect. FEMA's guidelines state that for dune removal "the profile is modified with a 1:50 seaward-dipping [slope] from the backside (landward) of the dune through the dune toe" [20]. The guidelines for defining the dune toe on the seaward face of the dune include "the junction between the relatively steep slope of the front dune and the noticeably flatter seaward region of the beach" or the elevation consistent with the local 10% SWEL [20]. The seaward-dipping slope of the eroded profile appears to have been specified at approximately 1:20, which is steeper than FEMA's guidelines (Figure 5.3). Assuming that the backside of the dune should be located within the limit of the PFD and FEMA's 1:50 slope suggests that the specified dune toe may warrant revaluation as depicted by the red dashed line in Figure 5.3. A dune toe assigned higher on the profile to align with FEMA's slope guidelines would result in a higher eroded profile which effects the wave runup and wave overtopping and potentially mapping of FEMA SFHA zones.

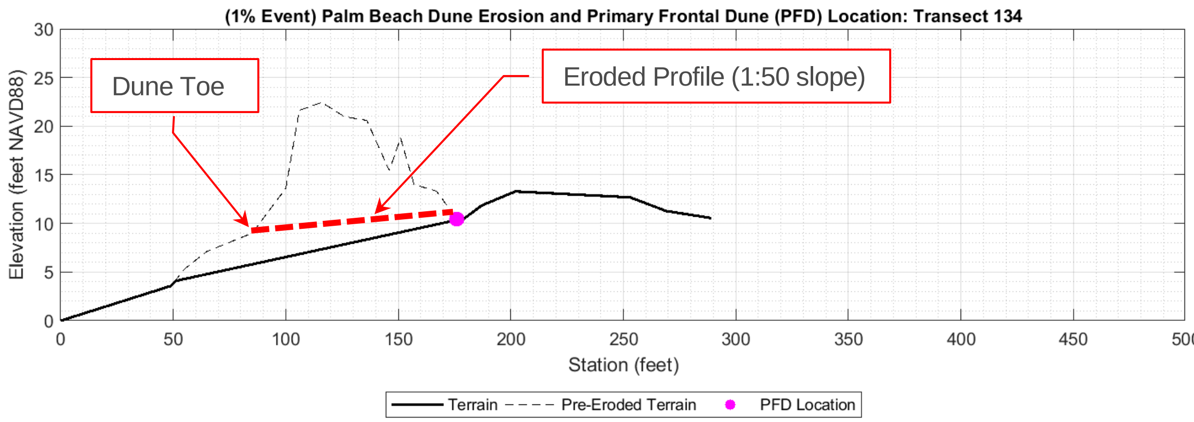


Figure 5.3: Dune Removal - Transect 134 (FEMA, 2019; [15]).

- Transect 136: Similar to Transect 134, FEMA identified dune removal for the transect and the eroded profile was specified steeper than the 1:50 FEMA guideline. A higher eroded profile associated with the dune toe specified at a higher elevation may reduce overtopping at the transect thereby having a significant effect on FEMA's mapping of the SFHA zone. This segment of coastline was mapped as an A0-1 Zone, which indicates sheet flow of water up to 1 foot across the dune during a 1% SWEL event.
- Transect 137 and 138: FEMA identified dune removal for the transects and the slope of the eroded profile was specified according to the FEMA guidelines (Figure 5.4). Inspection of the profile suggests that a dune toe at a higher elevation (+9 feet, NAVD88) may be justified. A higher dune toe would raise the elevation of the eroded profile (depicted by the red dashed line, Figure 5.4) and reduce wave runup and overtopping across the dune. This is the only segment of coastline within the County that the landward limit VE Zone was mapped based on the breaking wave height and the VE Zone extended across the barrier island into the Lake Worth Lagoon (Figure 5.5). Breaking waves across the barrier island may have implications further inland as larger waves within the lagoon may result in increased base flood elevations and in modifications to the delineated "limit of moderate wave action" along the lagoon's interior shorelines.
- Transect 147: The PFD was mapped within the pool of a single family residence (Figure 5.6). Revision to the PFD appears warranted to avoid this anomaly.
- Transect 158: A seawall is present, and the PFD was delineated. Within other segments of the County's coastlines (particularly south of Lake Worth Inlet) where seawalls were more prevalent, there appeared to be a tendency to not delineate the PFD and rely on the wave runup at a vertical structure to define the VE Zone. The presence of a seawall at this transect may warrant revaluation in defining the VE Zone to improve consistency throughout the County.

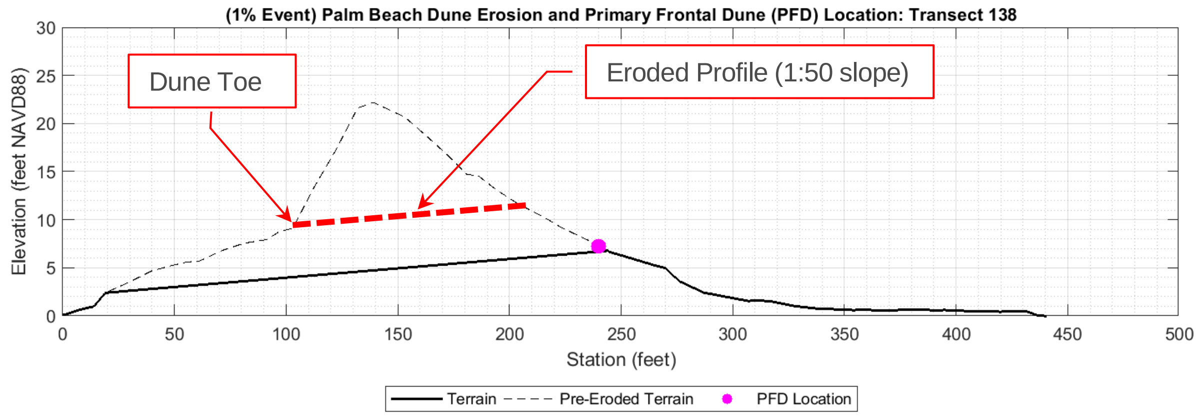


Figure 5.4: Dune Removal – Transect 138 (FEMA, 2019; [15]).

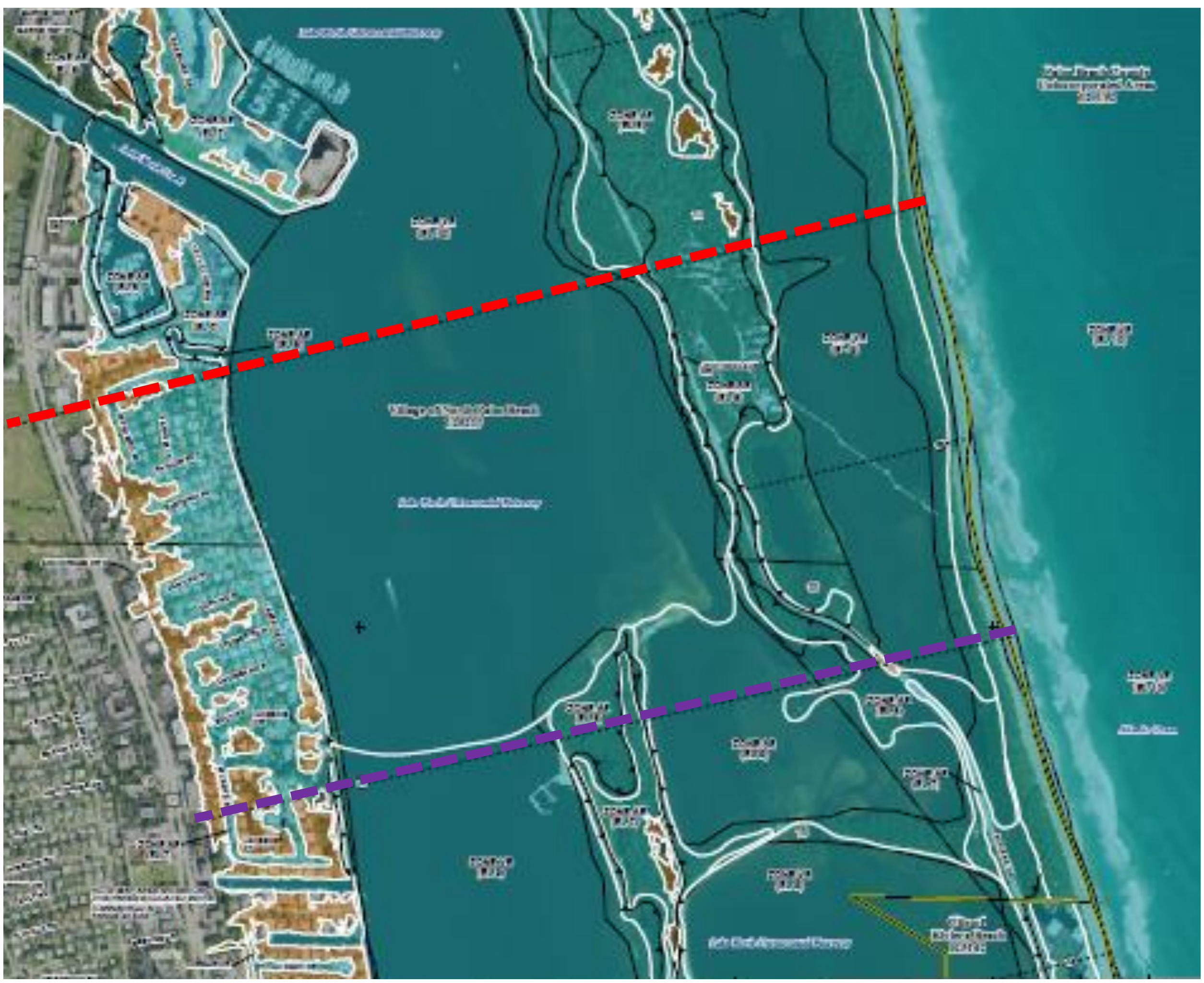


Figure 5.5: FIRM Panel 0383G (FEMA, 2019; [16]).
Transects 137 (purple) and 138 (red) highlighted by dashed lines.

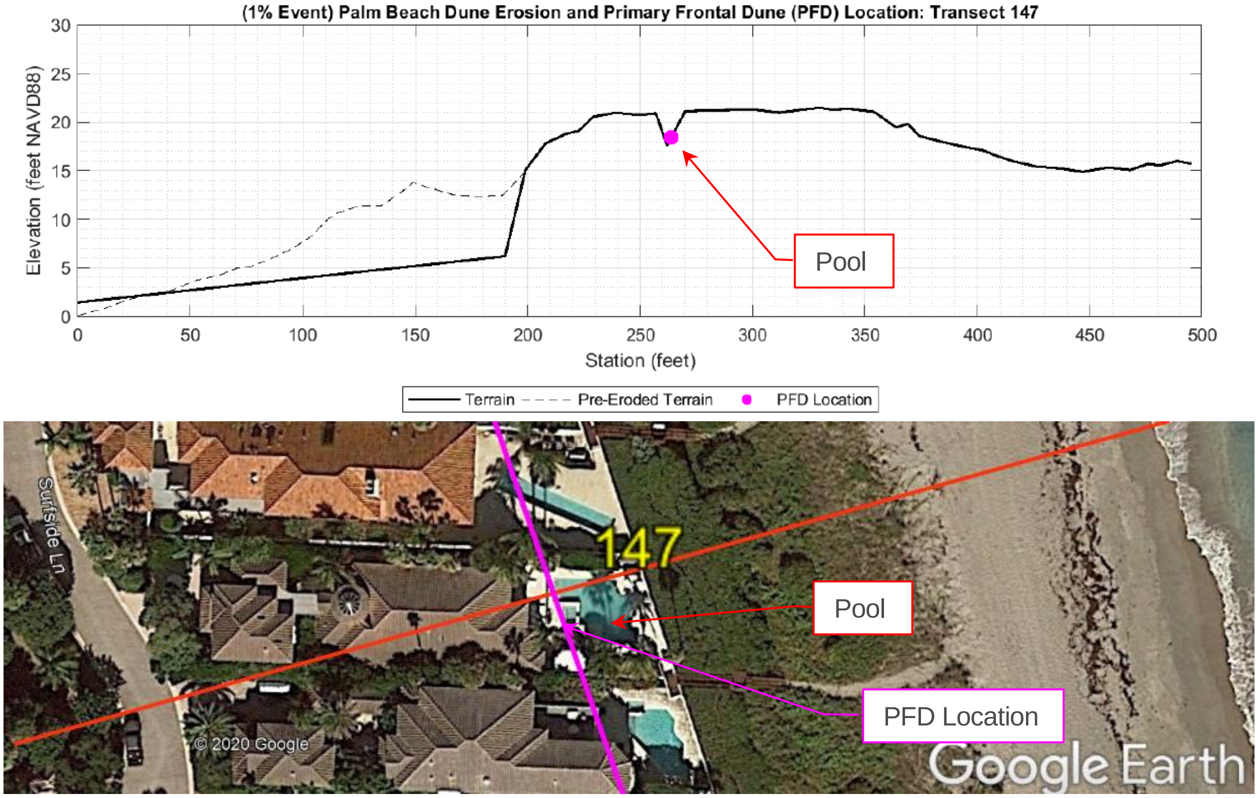


Figure 5.6: PFD – Transect 147 (FEMA, 2019; [15]).

5.2 Sheltered Waters

FEMA's analysis within sheltered waters evaluated overland wave propagation during coastal flooding events (e.g. 1% SWEL) along 30 transects. The transects were located within the Lake Worth Lagoon north of the East Ocean Avenue bridge in Lantana and within the Loxahatchee River. The transects within the Lake Worth Lagoon informed the mapping along the eastern shoreline. FEMA reported that sheltered water (inland) transects within the lagoon south of Lantana were "investigated for overland wave modeling, however, the inland wave conditions in these areas appeared to be influenced by nearby inlets, causing inconsistent mapping between the western and eastern shorelines" [14]. FEMA excluded sheltered water transects within the Lake Worth Lagoon south of the East Ocean Avenue and opted to rely on sheltered water transects to the north in mapping base flood elevations (BFE) along the eastern shoreline of the southern Lake Worth Lagoon.

Exclusion of the sheltered water transects in the southern Lake Worth Lagoon to avoid inconsistent mapping was noted by the FEMA's steering committee in its QC Review Documents. FEMA reported that larger starting wave conditions at the excluded transects, which appeared to be localized outliers as compared elsewhere in the lagoon, would have resulted in the mapping inconsistencies; higher BFE would have been defined along the eastern shoreline as compared to the western shoreline. The larger starting wave conditions, which were extracted from the SWAN+ADICR model results, were not resolved. In disagreement with the steering committee, the SFL study and mapping of the FIRM panels progressed by excluding the sheltered water transects in question. Additional review of FEMA's SWAN+ADCIRC modeling may be warranted to determine if the outlying starting wave conditions in the southern lagoon were related to the model mesh, wind and pressure fields, or other model parameters defined by FEMA (see Section 4.2).

6. Conclusions

FEMA's SFL study leveraged numerical modeling and analyses in an attempt to better define the coastal flood risks associated with storm surge. The document review presented above was intended to identify specific elements of the study that may have misrepresented the water levels and mapping of coastal flood risks with respect to Palm Beach County. The major elements are summarized below.

Validation Storm Selection

- Validation of the SWAN+ADCIRC model was based on five historical hurricanes; Betsy (1965), David (1979), Andrew (1992), Georges (1998), and Wilma (2005). Inclusion of these storms within the model validation may not have been appropriate given the magnitude of storm surge generated, the regional extents of the surge, the locations of gage measurements, and limited measured data. FEMA's statements within the documents also cast doubt as to the appropriateness of the selected storms.
- Inclusion of other validation storms in addition to (or in substitution of) those selected should be considered. For example, Hurricane Frances and Jeanne (2004) are potential storms for consideration.
  - The storms provide a basis for representing storm surges along the Atlantic coastline of the study area, specifically within Palm Beach County.
  - The storms were of historical significance to the study area as reported by FEMA.
  - The storms were used to validate the SWAN+ADCIRC model for FEMA's East Coast Central Florida (ECCFL) coastal study (2014). Inclusion within the SFL study may help improve agreement at the study area boundaries (Martin and Palm Beach county line).
  - The storms provide a basis for performing a wave validation, which was not performed for the study.

SWAN+ADCIRC Model Validation

- Model validation did not account for the location of measured data with respect to the distances from storm tracks, the type of measured data (e.g. hydrographs and HWM), or the timing between measured and modeled peak water levels. Failure to do so may have negatively affected model validation and uncertainties and resulted in water levels that are not representative.
- Hurricane Wilma was the only common validation storm presented between the SFL and ECCFL studies. The same water level gages were not used in both studies, which FEMA did not provide justification. The modeled water levels were on average greater than the measured data for both studies within the 60-mile segment of coastline common between the studies; but the average modeled differences for the SFL study were 64% greater than the ECCFL study. The ECCFL study ultimately eliminated Hurricane Wilma to improve the model's capability to reproduce non-exiting storm conditions and because of increased uncertainty in the wind and pressure fields for exiting storms. Despite this, Hurricane Wilma was included in the SFL study.
- The model uncertainty within Palm Beach County was the lowest of the four counties and 60% less than the uncertainty applied for the study. The greatest uncertainties were realized within Miami-Dade and Monroe Counties, which were attributed to Hurricanes Andrew and Wilma, respectively. Model bias was assessed by FEMA to determine whether the model validation tended to over or under predict water levels. The average of the overall study area reported by FEMA was estimated at -0.25 feet, which FEMA explained as a slight model bias in under predicting water levels. Within Miami-Dade County, the average was -0.52 feet which can be largely attributed to the landfall of Hurricane Andrew in Miami. Within Palm Beach County, the average was +0.25 feet suggesting an over prediction of modeled water levels. No adjustments were made by FEMA to account for spatial variability of model bias within the study area or the influence of the apparent outlier (Miami-Dade County).

Statistical SWEL

- The JPM-OS method was applied to the SFL study and is cited as FEMA's preferred method based on the agency's 1988 publication on Coastal Flooding Hurricane Storm Surge Model [10]. The JPM-OS method requires numerous steps and statistical parameterizations, which makes it difficult to identify the elements that the greatest effect on the model, but several were noted. These elements included storm forward speed and wind field asymmetry, statistical stationarity across the study area, dynamic modeling of tides in generating synthetic storm events, separate JPM-OS analysis for "east" and "west" coast storms, and meteorological and tidal optimizations. New advances in methodology for describing long duration hurricane climatology and joint probability for estimation of low probability inundation have been applied and approved by FEMA elsewhere within a single approach. For example, FEMA applied a Monte Carlo approach for a coastal study in North Carolina (2008) and approved use of this method in FEMA Guidance No. 8-12 (2012). Justification was not provided for not applying more advanced and newer approved FEMA approaches.
- Based on initial review of 1% SWEL as reported by FEMA, several locations within Palm Beach County were identified as areas that may warrant further consideration with respect to the developed model mesh.
- Model uncertainty was evaluated and used to statistically estimate the 1% SWEL within the study area. In developing inputs for the coastal hazard analysis, FEMA concluded that the 1% SWEL were high in some areas because of the model "uncertainty term and the combined storm frequency curves" for east and west coast storms used to define the 1% SWEL [14]. Review of FEMA's reports for the ECCFL study revealed that FEMA excluded west coast (exiting) storms citing that "exiting storms have a minimal effect on the low-frequency water levels" and "the presence of other uncertainties which influence the modeling results to a larger degree." FEMA reported that the influence of west coast (exiting) storms on the SFL study was 0.25 feet (3 times greater than the ECCFL study) but opted to include them regardless.
- At the study area Atlantic boundary between the SFL and ECCFL studies, discrepancies in the 1% SWEL were identified by FEMA. The 1% SWEL for the SFL study were higher by "1.7 feet along the open coast, 2.0 feet in the Intracoastal Waterway, and 2.0 to 4.2 feet up the Loxahatchee and North Fork Loxahatchee Rivers" [12]. FEMA identified a transition area and applied adjustments lowering the 1% SWEL within the northern 5 miles of the County to join the studies. Refinement to FEMA's approach to define adjustments to the 1% SWEL and to consider the entirety of the County in assigning those adjustments appears justified. The alternate approach presented herein, if adopted by FEMA, would result in lower 1% SWELs within the County.

Coastal Hazard Analysis

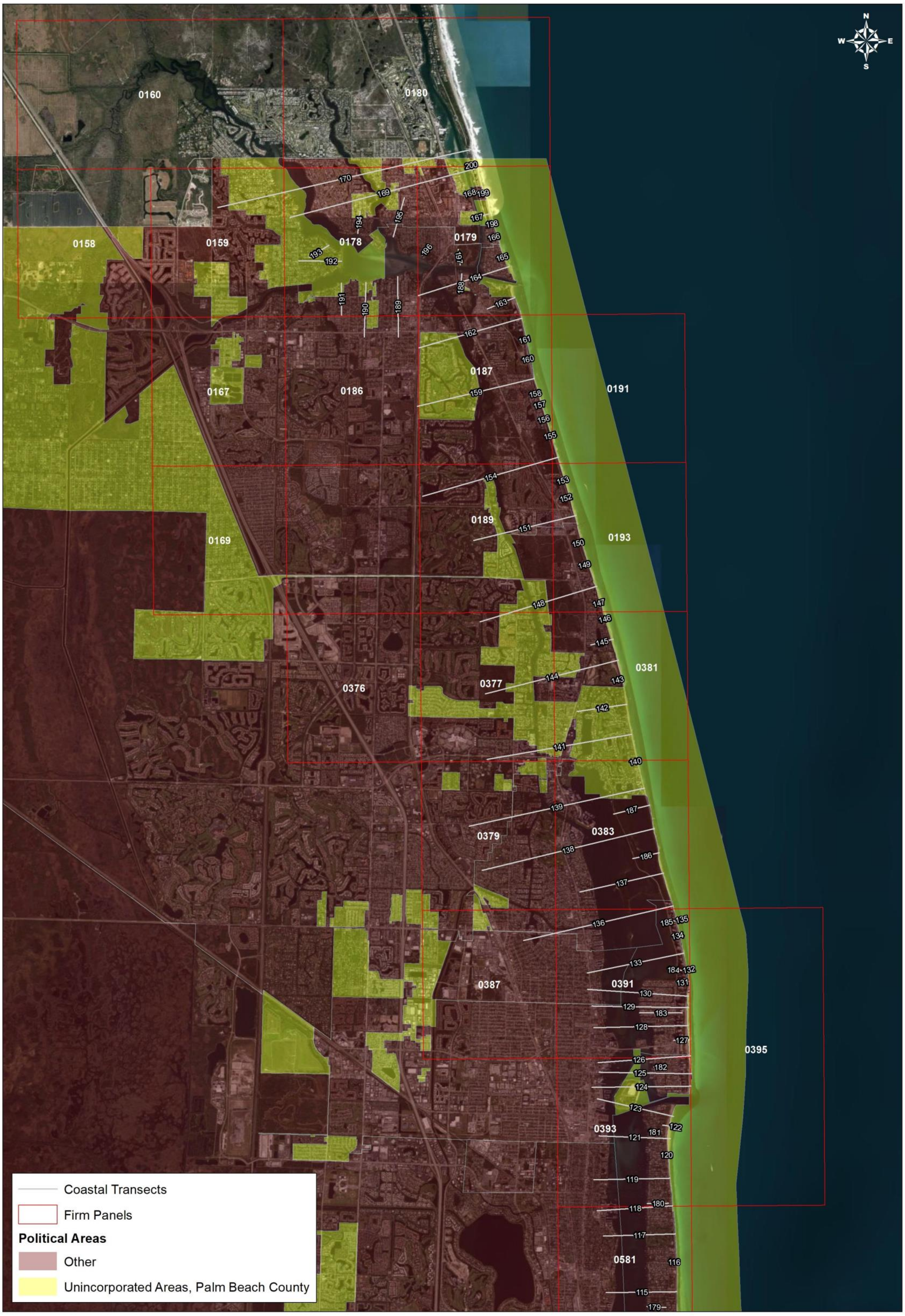
- Revisions to the 1% SWEL may affect FEMA's evaluation of dune response.
- FEMA's WHAFIS modeling assumed that the direction of wave propagation was shore normal (perpendicular to shore) and that the peak wave height coincided with the peak water surface elevation. While not necessarily an incorrect assumption, FEMA did not provide justification for these assumptions and if inappropriate can result in an overestimation of the wave conditions (e.g. wave heights) at the shoreline.
- Review of FEMA's analysis and inspection of open coast transects along the Atlantic coastline suggested there may be opportunities to improve the consistency of the mapping of the VE Zone throughout Palm Beach County and reflect the potential for wave overtopping and the landward limit of moderate wave action. These opportunities include the following.
  - The dune toe, landward limit of the dune crest, eroded profile, and the presence of seawalls could be defined to more consistently align with FEMA guidelines and represent coastal features. Inconsistencies at Transects 134, 136-138, 147, and 158 were noted specifically. Further review of FEMA's modeling is needed to determine if similar inconsistencies exist elsewhere.

- The PFD defined by FEMA is more often the most landward parameter used by FEMA to map the VE zone along the open coast. The PFD was located further seaward relative to the beach profile in the southern portions of the County as compared to the northern portions. Lake Worth Inlet was identified as the demarcation where the mapping inconsistencies began.
- FEMA's analysis of sheltered water (inland) transects excluded transects within the Lake Worth Lagoon south of the East Ocean Avenue bridge in Lantana to avoid inconsistencies in mapping BFE along the eastern shoreline. The inconsistencies were attributed to the larger starting wave conditions extracted from the SWAN+ADCIRC model results which appeared to be localized outliers as compared the other areas of the lagoon. FEMA opted to rely on sheltered water transects within the lagoon to the north for mapping purposes as opposed to reviewing the SWAN+ADCIRC modeling to resolve the outlying starting wave conditions.

Task 5 will complement Task 4 of our review. Task 5 will review the model setups, inputs, outputs, and other data provide by FEMA to delve beyond the level of detail of contained in FEMA's documents; this will provide the County additional information and details.

Appendix A

Coastal Hazard Analysis Transects



0 1 2 3 km

0 0.5 1 1.5 mi

Political Areas - Map 01

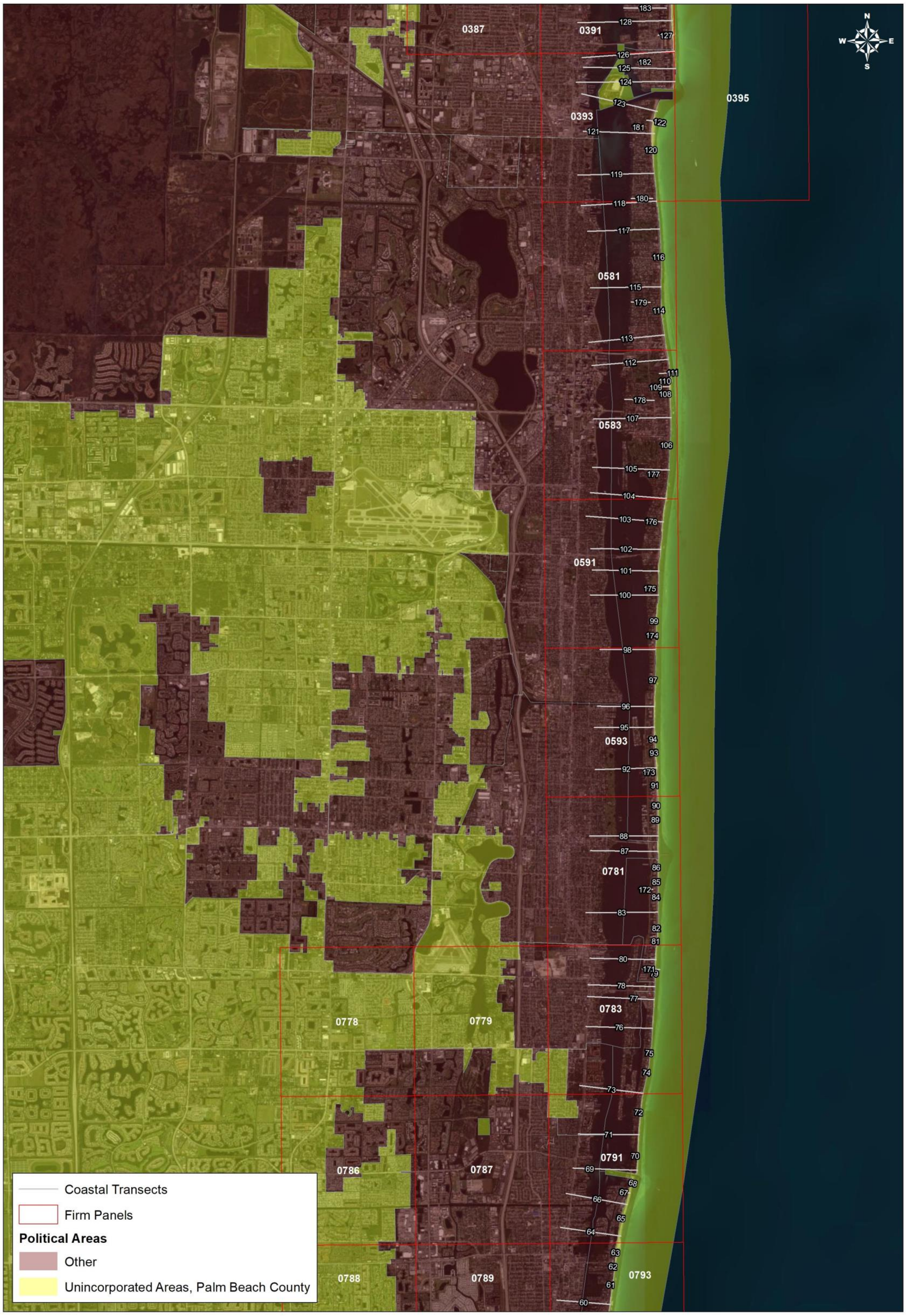
PALM BEACH COUNTY, FLORIDA

Imagery: ESRI World Basemap
Spatial Reference:
NAD 1983 StatePlane Florida East FIPS 0901 Feet

Baird.

13134PalmBeach - Political Boundary Rev02.mxd

Map Published: 2020-05-01



0 1 2 3 km

0 0.5 1 1.5 mi

Political Areas - Map 02

PALM BEACH COUNTY, FLORIDA

Imagery: ESRI World Basemap
Spatial Reference:
NAD 1983 StatePlane Florida East FIPS 0901 Feet

Baird.

Map Published: 2020-05-01

13134PalmBeach - Political Boundary Rev02.mxd

0 1 2 3 km

0 0.5 1 1.5 mi

Political Areas - Map 03

PALM BEACH COUNTY, FLORIDA

Imagery: ESRI World Basemap
Spatial Reference:
NAD 1983 StatePlane Florida East FIPS 0901 Feet

Baird.

Map Published: 2020-05-01

13134PalmBeach - Political Boundary Rev02.mxd

Appendix B

Primary Frontal Dune Analysis

Open Coast Transect	Erosion Method	Runup Method	1% SWEL (ft, NAVD88)	Runup[1] (ft, NAVD88)	Eroded Profile Crest (ft, NAVD88)	Primary Frontal Dune (PFD)	VE Zone Defined By
1	Structure	Runup2.0	6.99	12.34	13.80	Delineated	PFD
2	Dune Retreat	Runup2.0	6.87	12.42	12.90	Delineated	PFD
3	Structure	Runup2.0	6.90	12.06	10.60	Delineated	Runup
4	Dune Retreat	Runup2.0	6.91	11.35	12.80	Delineated	PFD
5	Dune Retreat	Runup2.0	7.00	10.96	12.30	Delineated	PFD
6	Dune Retreat	Runup2.0	6.75	12.67	17.60	Delineated	PFD
7	Dune Retreat	Runup2.0	7.01	12.79	13.70	Delineated	PFD
8	Dune Retreat	Runup2.0	6.87	12.44	16.60	Delineated	Runup
9	Dune Retreat	Runup2.0	6.76	12.41	15.00	Delineated	Runup
10	Structure	Runup2.0	6.88	12.61	12.80	Delineated	PFD
11	Dune Retreat	Runup2.0	6.54	12.41	25.90	Delineated	PFD
12	Dune Retreat	Runup2.0	6.65	12.30	22.80	Delineated	PFD
13	Dune Retreat	Runup2.0	6.60	11.94	24.00	Delineated	PFD
14	Dune Retreat	Runup2.0	7.04	13.16	20.30	Delineated	PFD
15	Dune Retreat	Runup2.0	6.81	11.73	28.00	Delineated	PFD
16	Dune Retreat	Runup2.0	6.74	12.27	22.94	Delineated	Runup
17	Dune Retreat	Runup2.0	6.84	12.16	19.23	Delineated	Runup
18	Dune Retreat	Runup2.0	6.82	12.05	20.00	Delineated	Runup
19	Dune Retreat	Runup2.0	6.86	11.84	16.67	Delineated	Runup
20	Dune Retreat	Runup2.0	6.82	11.38	17.03	Delineated	Runup
21	Dune Retreat	Runup2.0	6.83	11.27	16.73	Delineated	Runup
22	Dune Retreat	Runup2.0	6.79	12.61	26.84	Delineated	PFD
23	Structure	SPM	6.79	12.46	14.00		Runup
24	Dune Retreat	Runup2.0	6.80	11.65	15.83	Delineated	PFD
25	Dune Retreat	Runup2.0	6.70	12.01	19.36	Delineated	PFD
26	Dune Retreat	Runup2.0	6.90	11.90	16.07	Delineated	PFD
27	Dune Retreat	Runup2.0	6.77	11.62	18.47	Delineated	PFD
28	Dune Retreat	Runup2.0	6.82	11.80	17.45	Delineated	PFD
29	Dune Retreat	Runup2.0	6.75	11.79	14.26	Delineated	Runup
30	Structure	Runup2.0	6.80	11.56	15.10	Delineated	Runup
31	Structure	Runup2.0	6.80	11.51	14.40	Delineated	Runup
32	Structure	Runup2.0	6.77	11.55	13.60	Delineated	Runup
33	Structure	Runup2.0	6.89	11.64	13.70	Delineated	Runup
34	Dune Retreat	Runup2.0	6.99	11.65	18.54	Delineated	Runup
35	Structure	Runup2.0	6.60	11.45	14.90	Delineated	Runup
36	Dune Retreat	Runup2.0	6.88	11.70	15.02	Delineated	PFD
37	Dune Removal	Runup2.0	7.02	12.41	19.95	Delineated	Runup
38	Dune Removal	Runup2.0	6.87	11.89	14.71	Delineated	PFD
39	Dune Removal	Runup2.0	6.84	12.05	15.26	Delineated	PFD
40	Dune Removal	Runup2.0	6.94	11.74	13.58	Delineated	PFD
41	Dune Removal	Runup2.0	7.00	11.84	14.30	Delineated	PFD
42	Dune Retreat	Runup2.0	6.98	11.74	16.30	Delineated	PFD
43	Dune Retreat	Runup2.0	6.67	11.88	16.36	Delineated	PFD
44	Dune Retreat	Runup2.0	6.66	11.97	14.05	Delineated	PFD
45	Dune Retreat	Runup2.0	6.60	11.58	13.62	Delineated	PFD
46	Dune Retreat	Runup2.0	6.60	11.60	15.39	Delineated	PFD
47	Dune Retreat	Runup2.0	6.80	11.41	13.99	Delineated	Runup
48	Structure	Runup2.0	6.72	11.27	10.60	Delineated	Runup
49	Structure	SPM	6.77	11.21	10.76	Delineated	Runup
50	Structure	SPM	6.77	12.40	10.53	Delineated	PFD
51	Structure	SPM	6.77	13.05	10.30	Delineated	PFD
52	Dune Retreat	Runup2.0	6.74	10.92	14.49	Delineated	Runup
53	Structure	SPM	6.79	11.84	11.65	Delineated	PFD
54	Dune Retreat	Runup2.0	6.57	10.78	17.94	Delineated	PFD
55	Dune Retreat	Runup2.0	6.49	10.97	18.24	Delineated	PFD
56	Dune Retreat	Runup2.0	6.54	11.33	17.39	Delineated	PFD
57	Dune Removal	Runup2.0	6.47	11.32	10.79	Delineated	Runup
58	Dune Removal	Runup2.0	6.51	11.14	9.35	Delineated	Runup
59	Dune Removal	Runup2.0	6.47	11.32	9.33	Delineated	Runup
60	Dune Removal	Runup2.0	6.52	11.30	11.89	Delineated	Runup
61	Dune Retreat	Runup2.0	6.71	11.68	19.01	Delineated	PFD
62	Dune Retreat	Runup2.0	6.82	12.42	19.62	Delineated	PFD
63	Dune Retreat	Runup2.0	6.84	12.37	18.85	Delineated	Runup
64	Dune Retreat	Runup2.0	6.73	10.21	19.01	Delineated	Runup
65	Dune Retreat	Runup2.0	6.54	9.45	16.03	Delineated	Runup
66	Dune Retreat	Runup2.0	6.81	9.47	13.44	Delineated	Runup
67	Dune Retreat	Runup2.0	6.78	9.48	13.68	Delineated	Runup
68	Dune Removal	Runup2.0	6.83	9.15	12.97	Delineated	PFD
69	Dune Removal	Runup2.0	6.75	10.53	15.72	Delineated	Runup
70	Dune Removal	Runup2.0	6.62	10.92	11.64	Delineated	PFD
71	Dune Removal	Runup2.0	6.74	11.03	19.71	Delineated	Runup
72	Dune Removal	Runup2.0	6.80	11.12	18.33	Delineated	Runup
73	Structure	SPM	6.70	13.13	12.55		Runup
74	Structure	SPM	6.67	13.71	12.48		Runup
75	Structure	SPM	6.56	13.03	13.37		Runup
76	Structure	SPM	6.60	13.13	14.79		Runup
77	Structure	SPM	6.48	12.28	12.40		Runup
78	Structure	SPM	7.30	14.57	12.34		Runup
79	Structure	SPM	7.29	13.69	16.04		Runup
80	Structure	SPM	6.98	14.32	16.02		Runup
81	Structure	SPM	6.36	11.10	18.80		Runup
82	Dune Retreat	Runup2.0	6.37	10.52	16.90	Delineated	Runup
83	Dune Retreat	Runup2.0	6.36	10.52	17.70	Delineated	PFD
84	Dune Retreat	Runup2.0	6.39	10.52	18.80	Delineated	PFD
85	Structure	SPM	7.10	12.41	16.90		Runup
86	Dune Retreat	Runup2.0	6.46	10.61	15.70	Delineated	PFD
87	Dune Retreat	Runup2.0	6.50	10.53	14.60	Delineated	PFD
88	Dune Retreat	Runup2.0	6.80	10.95	15.00	Delineated	PFD
89	Structure	Runup2.0	6.75	11.27	12.80	Delineated	PFD
90	Dune Retreat	Runup2.0	6.53	10.83	16.50	Delineated	PFD
91	Dune Retreat	Runup2.0	6.48	10.53	10.00	Delineated	Runup
92	Dune Retreat	Runup2.0	6.32	10.49	15.70	Delineated	PFD
93	Dune Retreat	Runup2.0	6.64	10.87	20.40	Delineated	PFD
94	Structure	SPM	6.71	11.55	14.20		Runup
95	Dune Retreat	Runup2.0	6.44	10.97	24.00	Delineated	PFD
96	Dune Retreat	Runup2.0	6.39	10.68	22.70	Delineated	PFD
97	Structure	TAW	6.24	13.51	16.61		Runup
98	Structure	TAW	6.31	14.39	18.97		Runup
99	Structure	TAW	6.37	14.20	17.62		Runup
100	Structure	Runup2.0	6.38	11.17	17.01		Runup

Open Coast Transect	Erosion Method	Runup Method	1% SWEL (ft, NAVD88)	Runup[1] (ft, NAVD88)	Eroded Profile Crest (ft, NAVD88)	Primary Frontal Dune (PFD)	VE Zone Defined By
101	Dune Retreat	Runup2.0	6.28	10.52	16.10	Delineated	PFD
102	Structure	SPM	6.38	11.09	11.60		Runup
103	Structure	SPM	6.43	10.61	11.50		Runup
104	Structure	Runup2.0	6.49	10.56	13.71		Runup
105	Structure	Runup2.0	6.54	10.63	16.70		Runup
106	Structure	Runup2.0	6.47	9.90	15.90		Runup
107	Structure	Runup2.0	6.32	10.33	15.20	Delineated	PFD
108	Dune Retreat	Runup2.0	6.48	9.84	14.40	Delineated	PFD
109	Structure	TAW	6.25	17.11	14.11		Runup
110	Structure	Runup2.0	6.24	10.21	11.69		Runup
111	Structure	SPM	6.20	13.13	16.00		Runup
112	Structure	Runup2.0	6.29	10.70	14.50	Delineated	Runup
113	Structure	Runup2.0	6.40	11.13	12.20		Runup
114	Structure	SPM Curved Runup	6.47	15.86	14.00		Runup
115	Structure	Runup2.0	6.41	11.67	15.60		Runup
116	Structure	Runup2.0	6.33	15.63	17.30		Runup
117	Structure	Runup2.0	6.33	14.31	16.10		Runup
118	Structure	Runup2.0	6.34	12.81	13.90		Runup
119	Structure	Runup2.0	6.59	13.59	14.90		Runup
120	Dune Retreat	Runup2.0	6.67	14.20	12.66	Delineated	Runup
121	Dune Retreat	Runup2.0	6.61	10.59	13.69	Delineated	Runup
122	Dune Removal	Runup2.0	6.62	10.12	11.22	Delineated	PFD
123	Dune Removal	Runup2.0	6.42	10.13	11.06	Delineated	PFD
Lake Worth Inlet							
124	Dune Retreat	Runup2.0	6.07	12.65	14.35	Delineated	PFD
125	Dune Retreat	Runup2.0	6.15	10.24	15.78	Delineated	PFD
126	Dune Retreat	Runup2.0	6.32	9.54	13.00	Delineated	PFD
127	Dune Retreat	Runup2.0	6.36	9.58	10.82	Delineated	PFD
128	Dune Retreat	Runup2.0	6.45	10.48	11.35	Delineated	PFD
129	Dune Removal	Runup2.0	6.46	10.63	9.76	Delineated	PFD
130	Dune Removal	Runup2.0	6.43	10.52	9.12	Delineated	PFD
131	Dune Removal	Runup2.0	6.20	9.62	6.62	Delineated	Runup
132	Structure	Runup2.0	6.15	10.89	22.00	Delineated	PFD
133	Dune Retreat	Runup2.0	6.15	10.54	22.81	Delineated	PFD
134	Dune Removal	Runup2.0	6.18	10.20	13.29	Delineated	PFD
135	Structure	SPM	6.19	10.27	18.70	Delineated	PFD
136	Dune Removal	Runup2.0	6.14	9.88	9.48	Delineated	Runup
137	Dune Removal	Runup2.0	6.36	9.98	7.38	Delineated	Breaking Wave Ht
138	Dune Removal	Runup2.0	6.22	9.77	6.77	Delineated	Breaking Wave Ht
139	Dune Retreat	Runup2.0	6.20	10.62	19.41	Delineated	PFD
140	Dune Retreat	Runup2.0	6.19	10.64	17.33	Delineated	PFD
141	Dune Retreat	Runup2.0	6.22	10.87	18.88	Delineated	PFD
142	Dune Retreat	Runup2.0	6.22	10.07	10.63	Delineated	Runup
143	Dune Retreat	Runup2.0	6.20	9.96	18.12	Delineated	PFD
144	Dune Retreat	Runup2.0	6.19	9.81	21.20	Delineated	PFD
145	Dune Retreat	Runup2.0	6.30	10.02	17.07	Delineated	PFD
146	Dune Retreat	Runup2.0	6.30	9.65	14.07	Delineated	PFD
147	Dune Retreat	Runup2.0	6.20	9.59	20.96	Delineated	PFD
148	Structure	Runup2.0	6.32	9.85	16.40	Delineated	PFD
149	Dune Retreat	Runup2.0	6.30	9.71	15.02	Delineated	PFD
150	Dune Retreat	Runup2.0	6.30	9.49	22.56	Delineated	PFD
151	Dune Retreat	Runup2.0	6.30	9.79	23.37	Delineated	PFD
152	Dune Retreat	Runup2.0	6.20	9.49	22.73	Delineated	PFD
153	Dune Retreat	Runup2.0	6.22	9.69	13.06	Delineated	PFD
154	Dune Retreat	Runup2.0	6.16	9.18	22.30	Delineated	PFD
155	Dune Retreat	Runup2.0	5.97	9.29	15.98	Delineated	PFD
156	Dune Retreat	Runup2.0	6.08	9.18	15.62	Delineated	PFD
157	Dune Retreat	Runup2.0	6.21	9.27	14.69	Delineated	PFD
158	Structure	SPM	5.73	12.27	12.72	Delineated	PFD
159	Dune Retreat	Runup2.0	5.89	8.50	23.26	Delineated	PFD
160	Dune Retreat	Runup2.0	5.98	8.75	13.89	Delineated	PFD
161	Dune Retreat	Runup2.0	5.81	8.50	18.61	Delineated	PFD
162	Dune Retreat	Runup2.0	5.77	7.91	20.61	Delineated	PFD
163	Dune Retreat	Runup2.0	5.79	7.60	13.07	Delineated	PFD
164	Dune Retreat	Runup2.0	5.69	7.83	14.31	Delineated	PFD
165	Dune Retreat	Runup2.0	5.80	8.17	17.23	Delineated	PFD
166	Structure	TAW	5.58	12.12	14.57	Delineated	PFD
167	Dune Retreat	Runup2.0	5.69	9.35	17.07	Delineated	PFD
168	Dune Retreat	Runup2.0	5.59	9.43	17.91	Delineated	PFD
169	Dune Retreat	Runup2.0	5.57	9.27	17.91	Delineated	PFD
170	Dune Removal	Runup2.0	5.45	8.81	6.25	Martin County	N/A

[1]Runup capped at 3 feet above the eroded profile crest elevation for Transects 109, 131, and 138 [14].

Coastline (Open Coast Transects)	# of Transects			% of Transects	
	Open Coast	PFD Delineated	VE Zone Defined by PFD	PFD Delineated	VE Zone Defined by PFD
South of Lake Worth Inlet (1 to 123)	123	92	54	75%	44%
North of Lake Worth Inlet (124 to 170)	47	46	41	98%	87%
Palm Beach County (1 to 170)	170	138	95	81%	56%